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Paper 978 AT 2

JOURNAL
AIR TRANSPORT DIVISION
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THE EFFECT OF AIRPORT DISTANCE ON TRAFFIC GENERATION

James C. Buckley*

On October 13, 1955, Pan-American World Airways announced that it had placed an order for 45 turbo-jet aircraft with two domestic aircraft manufacturers. Similar orders by several other United States airlines are in early prospect for jet aircraft to be operating in four to five years on domestic as well as overseas routes.

On July 26, 1955, Capital Air Lines inaugurated the first service with turbo-prop aircraft on United States domestic routes when it began operations with the British Viscount on its Washington-Chicago and Washington-Norfolk routes.

These two developments in 1955 bring into sharp relief the problem of adjustment which must be accomplished within the next few years between the requirements of turbo-prop and turbo-jet aircraft on the one hand, and the facilities at major commercial airports on the other.

It is not the purpose of this paper to evaluate the problem posed by jet aircraft, either with respect to landing area and air space requirements, or with respect to the influence on surrounding areas of the noise-nuisance which currently accompanies jet operation. I am personally convinced that major penetration of the domestic air transportation market by turbo-jet aircraft will require production of such aircraft with landing area requirements reasonably within present recommended standards, and with a noise level which can be tolerated at existing airports, - and I am further convinced that the manufacturers can and will have to find means to provide such aircraft.

The purpose of this paper, however, is to call attention to the fact that current discussions about jet aircraft are likely to strengthen a tendency among engineers and laymen alike to think today only in terms of the development of new outlying airports rather than the redevelopment of close-in airports; and to suggest that there are strong indications both from the standpoint of the community and from the standpoint of the maximum development of air transportation generally to indicate the importance of giving equal or greater consideration to the possibility of redeveloping and expanding close-in airport locations.

Note: Discussion open until October 1, 1956. Paper 978 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 82, No. AT 2, May, 1956.

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While the general subject of this paper is the effect of airport distance on air traffic generation, I shall also discuss briefly the effect of airport distance on a community's economy, and the extent to which a community may be able to afford to pay a premium price for a close-in airport.

The Effect of Airport Distance on Air Traffic Generation

Unlike matured thinking on marketing of other goods and services, there is a disposition to feel that the place of offering of air service does not substantially affect the quantity of that service purchased by consumers. Thus, even businessmen who regard location as a vital factor in their own businesses may be led to disregard the same factor when thinking about airports.

To a considerable extent, the effect of airport distance on traffic generation has failed to be appreciated because there have been so little data available to illustrate and establish such effects. They can, of course, be measured on either of two general bases. These are:

1) By examining changes in air traffic generation at major air transportation centers on a "before and after" basis, where there has been a major change in the airport distance.
2) By examining air traffic generation in relation to population in areas near and areas distant from a given airport or group of airports at a particular point in time.

Evaluations based on a "before and after approach", are limited because there have been very few major air traffic centers in the country where there has been a major change in airport distance with a sufficient history of results to justify a conclusion.

Evaluations based on air traffic generation in relation to population at varying distances from a given airport or airports at a given point in time are even more difficult because so little data has ever been assembled on the local origins and destinations of air passengers.

It has been possible, however, in the course of work on several airport and air transportation projects to evaluate pertinent data on a group of situations covering both types of measurement, and the results and implications of these evaluations will be discussed here. They are important because of their uniform implication that a very substantial volume of air traffic is lost because of airport distance. The cases on which data have been assembled and evaluated are as follows:

1) The effect on a major segment of the Detroit air travel market from the removal of its airline airport from a location 6 miles from the City center to a location 31 miles from the City Center.
2) The relationship between air traffic generation and population at 21 California airports as between the population less than 10 miles from each airport and the population 10 to 20 miles from each airport.
3) The relationship between air traffic generation and population within the City of Dallas as between areas close to the airline airport and areas distant from airline airport.
4) The relationship between air traffic generation and population as between areas less than 15 miles from the Buffalo airport and areas 25 miles from that airport.

The Detroit Experience

Early in 1947 scheduled airline operations at Detroit were moved from the Detroit Municipal Airport, 6 miles northeast of downtown Detroit, to the Willow Run Airport, 31 miles west of the city. The Willow Run Airport is 12 miles from Ann Arbor, a city of 48,000, and only 3 miles from Ypsilanti, a city of 18,000, both of which could be expected to contribute more traffic at Willow Run than at the old airport. A limited access expressway connects Detroit with Willow Run Airport.

Sufficient time has elapsed to evaluate the effect of this airport move and to determine answers to the following questions:

A) Were any passengers lost to air transportation at Detroit as a result of the change in airport location?
B) If so, were these passengers ever regained?

A measurement of changes in passenger development at Detroit by itself would not be sufficiently refined since some changes would be expected even if the airport had not been changed. A better measurement would relate changes in passenger development at Detroit to the normal trend of the market as indicated by developments in another, or control, group of cities. The control group should not, of course, contain cities of too different a size in relation to Detroit nor from sections of the country undergoing very different growth patterns since 1946.

A control group was established, therefore, consisting of all standard metropolitan areas of more than 500,000 population within 300 miles of Detroit. The cities constituting the control group were Buffalo, Chicago, Cincinnati, Cleveland, Columbus, Indianapolis, Milwaukee, Pittsburgh and Youngstown. In September, 1946, before the airport move, Detroit's originating and terminating traffic with these cities was 53.2% of its total originating and terminating traffic, but in September, 1954, it amounted to only 37.9%.

The universe of traffic pairs to be considered in the analysis was made up of 45 different traffic pairs, considered in two groups, as follows:

1) The nine traffic pairs consisting of Detroit paired with each of the nine cities in the control group.
2) The 36 different traffic pairs consisting of each of the cities in the control group paired with each other such city.

The number of origin-destination passengers reported for each September for which C.A.B. data are available was compiled for each such pair. The city totals for the control group pairs (each such city paired with each other) and the grand total of control group pairs are shown on a time series graph in Plate I. It will be noted that the trend of the sum of the pairs is representative of the trends for the individual cities.

The sum of the Detroit pairs and the sum of the non-Detroit pairs are shown together on a similar time series graph in Plate II. It is apparent that the trend of passenger development at the city which moved its airport (Detroit) is different from the trend for the control group. From this graph it will be noted:

1) From 1940 to 1946 traffic development for the Detroit pairs and the control group pairs was parallel or at almost the same rate of growth.

2) From 1949 to 1954 traffic development for the Detroit pairs and the control group pairs was parallel or at almost the same rate of growth.
3) Only between 1946 and 1949 was there a significant difference in the trend. During this period the Detroit pairs declined, at first rapidly and then at a slower rate, while the control group pairs had a generally upward trend.

The conclusion to be drawn from these observations is that the effect of moving the airport at Detroit took three years to manifest itself fully in reduced passenger traffic, and that a normal rate of development then took over at the reduced level.

Why it should have taken three years for the effect to show itself fully can only be suggested. Apparently the manner in which air service is woven into the fabric of business and personal life in a modern metropolis is so complex that readjustments to changes in its place of offering can only be made gradually. As a group, the persons who travel most by air cannot, perhaps, suddenly give up that habit without making it more difficult to meet business and personal obligations. For a man who travels a lot, the location of the airport is a factor to consider in selecting a place to live, but a change in airports apparently does not mean he will sell and move the next day.

A summary has been prepared on the basis that the rate of traffic development was normal at Detroit from 1940 to 1946 and again from 1949 to 1953, but that from 1946 to 1949 traffic development was affected by the airport change, and that the control group experience best indicates what would have happened had service been available at the Detroit Municipal Airport throughout the entire period. Thus, for the three year adjustment period the trend of the control group has been used, whereas starting with 1949, the actual Detroit trend is reintroduced although at a new level. This is illustrated in Plate III.

The difference between the estimated traffic development as described above, and the actual traffic for the Detroit pairs is the measure of the loss of traffic with these pairs. The percentage loss of traffic normally to be expected at Detroit increased from 1946 to 1949 in which year it amounted to 46.3%. The history from 1949 to 1954 shows that this loss of available traffic has continued in a range from 39.7% to 49.0 %. There is every reason to expect that it will continue so long as air service is available only at a distance airport.

The California Examples

During the 14-day period, September 10-23, 1950, a survey was made by the Institute of Transportation and Traffic Engineering, University of California, in cooperation with American, Southwest, TWA, United and Western Air Lines, of passengers traveling in California on scheduled airlines. As stated in the introduction to the report, "Research Report No. 10-1, "published by the Institute in August, 1951, the primary purposes of the survey were to obtain data on the geographic distribution of homes of passengers and points of origin of ground trips to each airport. Summary data on the origin of ground trips were presented as Table A-8 of the report for all but two California airports.

The availability of the report made it possible to study the effect of airport distance on passenger generation rates at a sufficiently large number of

places to yield highly significant results. Obviously the economic characteristics of cities using any one airport might be so different that their per capita air passengers would not be good measures of the effect of distance on the generation of passengers. In the present case it has been possible, however, to study a large number of experiences where, for example, the larger cities are sometimes closer and sometimes farther away from the airports, so that the chance characteristics of communities are eliminated in the final result. The procedures employed were as follows:

1) Around each California airport were drawn two circles, one with a radius of 10 miles and the other with a radius of 20 miles. Any area which was within 20 miles of two or more separate airports was eliminated from consideration.
2) For each airport, all populated places reported by the U. S. Census of 1950 with 1,000 or more population, were assembled into two groups: those within 10 miles of the airport, and those more than 10, but within 20 miles from the airport.
3) The passengers reported by the survey of the Institute of Transportation and Traffic Engineering for each community were entered in the appropriate places.
4) The passenger generating rates per 1,000 population were then computed for the cities in the 0-10 mile zone and also for those in the 10-20 mile zone.
5) The passenger generating rate per 1,000 population in the 0-10 mile zone was taken as normal, assigned an index of 100.0, and, on this basis, the passenger generating rate index of the 10-20 mile zone was computed.

It was possible to carry out this comparison for a total of 21 airports in California. For the other airports, no comparison was possible, either because there were no places reported by the Census with 1,000 or more inhabitants in one or the other of the two mileage bands, or because no passengers had been reported for such places, or because all points within 20 miles of the airport were also within 20 miles of another airport.

A summary of the percentage loss in per capita passenger generation of communities 10-20 miles from the airport relative to communities 0-10 miles from the airport is given as Plate IV.

From Plate IV it will be noted that at all but two of the 21 California airports more than a 40% reduction in per capita passenger generation existed for communities 10-20 miles from their airports, and that the typical loss of these communities was from 60% to 80% as against communities closer to their airports. These relationships are long-term relationships, and reflect settled adjustment of communities to airport distances.

The Dallas Example

In connection with a general evaluation of its airport development program, the city of Dallas in December, 1951, conducted a carefully controlled sample survey of passengers enplaning and deplaning at its airline airport to determine, among other things, the local origins and destinations of passengers originating or terminating their journeys at Dallas. These data also included the length of air journey for each passenger interviewed. As a result, these data provide a basis for evaluating both the effect of airport

distance on air traffic generation and also the extent to which the length of the air travel itself may minimize this effect. The analysis was carried out as follows:

1) The local origins and destinations of Dallas' resident air passengers as indicated by a sample survey at Love Field were distributed by U. S. census tracts within the city and by length of air trip.
2) The relative air passenger potential of each Dallas census tract was computed by adjusting the family population in each tract for income. Higher income families were more heavily weighted than lower income families on the basis of a survey of travel habits of various income groups.
3) The census tracts were divided into ground distance bands from Love Field as nearly as possible into the following groups by miles: 0-2; 2-4; 4-8; 8-10; and 10-13.
4) The number of air passengers per thousand families (after adjustment for income) was computed for each ground distance band and for each length of air trip.
5) The computations were translated into a series of graphs, each one showing the effect of ground distance on passenger generation for a different length of air trip. Curves were fitted to the points. The curve for all trips is shown in Plate V.

The graphs show that for very short-haul air trips the loss of air passenger potential is only slightly greater than for medium and long-haul trips and that severe losses in air passenger potential occur with greater ground distance for all lengths of air trip. The following table shows these losses as between a ground haul of 2-4 miles and one of 10-13 miles.

Length of Air Trip (Miles)	Passengers per 1,000 Families (Adjusted for Family Income)		Percentage Loss of Air Passenger Potential
	2-4 Miles	10-13 Miles	
0-99	0.12	0.00	100.00
100-149	0.20	0.00	100.0
150-199	1.91	0.30	84.3
200-249	1.79	0.30	83.2
250-299	1.35	0.89	34.1
300-499	2.07	0.44	78.7
500-999	1.91	0.74	61.3
Over 1,000	2.15	0.44	79.5

These data with respect to the effect of airport distance on air traffic at Dallas certainly dissipate the notion that airport distance is not a factor affecting long-haul air travel. They reinforce the views of those who hold that travel, regardless of its distance, is only one facet of a complex of business and personal activity; and that it can be encouraged and discouraged, not merely lost to another form of transport. This view is not inconsistent with the finding, as at Dallas, that for very short-haul trips there is a somewhat greater loss of air passenger potential than for the medium and long-haul trips.

The Buffalo Example

Exhibits submitted by the City of Niagara Falls in the Niagara Falls Airport Case (CAB Docket No. 6125) indicated a sound factual basis for determining the effect of distance on air passenger generation in the Buffalo-Niagara Falls area. This was done by making a detailed analysis of 4,339 air trip insurance policies written at the Buffalo Airport in March and September 1952 and September 1953, in order to determine the incidence of air travel in relation to population for various distance zones around the Buffalo Airport. The results, which are shown pictorially in Plate VI, were as follows:

Distance from the Airport	Air Passengers per Thousand Population
Less than 15 miles	393
15 to 25 miles	245
More than 25 miles	84

The data establish the fact that the area lying 15 to 25 miles from the Buffalo Airport generates 37.7 % less air traffic in relation to population than the area within 15 miles of the airport.

Conclusions as to the Effect of Airport Distance on Air Traffic Generation

These examples covering experience in widely-separated parts of the country all lead to the conclusion that there is a demonstrable effect on air traffic generation from airport distance; that the effect is very substantial in terms of the difference between an airport five to seven miles away from major traffic concentrations and one fifteen miles or more distant; and that the increment of passengers lost appears to be on the order of 40 % or more. This lost traffic is probably far more valuable to the air carriers in terms of line-haul revenue, and to the community in terms of time and money savings and added attractiveness to industry, than any added expense which might be entailed in making a close-in airport suitable to accommodate needed scheduled airline services. To test this point, it will be worth while to consider the effect of airport distance on the economy of a community.

Effect of Airport Distance on the Community

While almost no data are available as to the comparative impact on communities of close-in and distant airports, a carefully documented study of this problem was made by the City of Dallas and submitted to the Civil Aeronautics Board in the so-called Reopened Fayetteville Proceeding, CAB Docket No. 5592 et al. The occasion was a hearing by the Civil Aeronautics Board on whether it should rescind an order which required a local service airline on one of its routes to serve Dallas through the Fort Worth International Airport, 18.3 miles distant from the Dallas city center, and prohibited service to Dallas on that route segment at the Dallas airport which is only 5-1/2 miles from the city center.

Data were submitted which show that the major concentrations of Dallas' air passengers and Dallas' air freight are immediately accessible to the Dallas airport and distant from the Fort Worth Airport. These data are portrayed in Plate VII and Plate VIII.

Data were also submitted on the basis of extensive test runs between all sections of the city and each of the two airports to establish the added time and and distance required between each portion of the city and the more distant airport. Indicative of the results of this investigation are the data portrayed in Plate IX which show that more than 92% of Dallas' air passengers would require more than 15 minutes additional ground time in each direction if they were to use the more distant airport.

Also submitted were detailed data which established that as a result of the use of its close-in airport, the Dallas economy is saving:

1/3 on airport limousine fares
Over 70% on taxicab fares to and from the airport
67% on private automobile expense to and from the airport
52.2 % on ground transportation time for air passengers
68.4 % of ground distance and associated costs for air freight

When these savings are expressed in dollars as a lowest common denominator they show the following:

Estimated Minimum Savings to the Dallas Economy From the Availability and Use of a Close-In Airport

Type of Air Traffic	1953	1955	1960
Air Passengers	$ 1,566,018	$ 1,752,366	$ 2,380,132
Air Freight	9,443	18,885	28,328
Air Mail	20,000	20,000	20,000
Total	$ 1,595,461	$ 1,791,251	$ 2,428,460

Impressive though these direct dollar savings to the community's economy are, it must be remembered that they are only a minimum estimate of the benefit to the community from the availability and use of a close-in airport because they give no effect to indirect benefits such as:

1) The value to the community of the airport's payroll, most of which is lost when the airport is situated at a distant point usually outside the city limits. At Dallas, for instance, the airline airport currently provides jobs for about 3,000 people with an annual payroll of close to $ 20,000,000.
2) The value to the community of the airport as an attractor of new industry which is lost with a distant airport which is usually outside the city limits. At Dallas, for example, the principal executive of the Trinity Industrial District has stated that the convenient availability of the airport has been a major factor in attracting several of their large tenants.
3) The value to the community of the airport as an aid to the competitive position of local business enterprises. Again, at Dallas, some banks maintain an hourly messenger service to and from the airport to expedite the clearance of checks moving via air mail to and from their correspondent banks in small and medium size communities. The bankers have said that they could not afford to perform this service,

which helps their business greatly, if they were required to use a distant airport.

There is no reason to believe that there is anything in the Dallas situation which is different from that which prevails at other major air traffic centers throughout the country. On the contrary, the factors which establish such substantial benefits to the Dallas economy from the availability and use of a close-in airport are factors common to most of the major metropolitan areas. In the light of these facts, it is hardly conceivable that either the engineer or the layman would wish any city to forego development or redevelopment of a close-in airport without a full evauation of the benefits which would be lost from its abandonment compared to the cost of its continuance. An example or two will illustrate the point even more clearly:

1) There is considerable concern currently about providing at each end of the principal runway of commercial airports the so-called Doolittle Clear Zone, - i.e. an area 1,000 feet wide and 2,640 feet long at each end of the runway. Most airports have been providing 1000 to 1200 feet of such clear area so that a given airport might face a requirement for securing additional land for both ends of its principal runway together of perhaps 2800 feet in length and 1000 feet in width, - or about 70 acres. If this were miscellaneous improved real estate such as might be found adjoining an airport five to seven miles from a city center, it might reasonably average out at $ 250,000 an acre, - or a total for the 70 acres of $ 17,500,000. While this appears at first blush to be a tremendous price to pay for 70 additional acres at an airport, it becomes almost a bargain at a community such as Dallas where it is less than 10 years saving to the community from the use of its close-in airport; and its expenditure saves the community the tremendous additional capital investment of acquiring land and developing a new airport at an outlying location.
2) Another example is one which many communities with close-in airports may face in the next ten years and that is the possible desirability of lengthening their principal runway by 1,000 or 2,000 feet for the better accommodation of jet aircraft. A 2,000 foot addition to an instrument runway, with a parallel taxiway and warm-up path, would require about 80 acres, which again might average out at about $ 250,000 per acre for miscellaneous improved real estate, or a $ 20,000,000 investment to acquire the needed land. Again, this apparently large expenditure for only 80 acres of land appears more of a sound business investment when it is remembered that it will permit the community to avoid developing a new airport which may cost $ 25,000,000 to $ 50,000,000; and when it continues annual benefits which, in a city like Dallas, will total as much in eight years by 1960 as the cost of this land required to keep the airport in use as a close-in facility.

CONCLUSION

The basic conclusion suggested from this study which has extended over the past several years is that too little attention has been paid by engineers, planners and laymen alike to the effect of airport distance on air

traffic generation, on the air carriers, and on the communities concerned. While the available pertinent data are not as extensively developed as one would like, they are uniformly indicative of the fact that:

1) There is a very substantial loss in air traffic when a community must accept its air service through a distant airport.
2) This loss in air traffic has a direct and detrimental effect on the revenues of the air carriers.
3) The communities concerned are put to a substantial added burden of determinable expense because of the necessity of using a distant airport, - a cost which appears substantially greater than the added costs of developing and extending close-in airports.
4) The communities using distant airports are placed under additional disadvantages by losing substantial ancillary benefits available only from close-in airports, such as a strong payroll within the city limits, a strong force for attracting new and expanded industry, and a strong factor in maintaining and improving the competitive position of local industry.

The implication of these facts from the standpoint of the engineer seems to me to be clearly to place on him in an airport location or relocation project the obligation to see to it that the community concerned evaluates on a sound basis the benefits of a close-in airport in relation to any alleged disadvantages, and compares these with the alleged benefits and demonstrable disadvantages of an outlying airport, before making any final determination to abandon the thought of developing or redeveloping close-in commercial airport facilities.

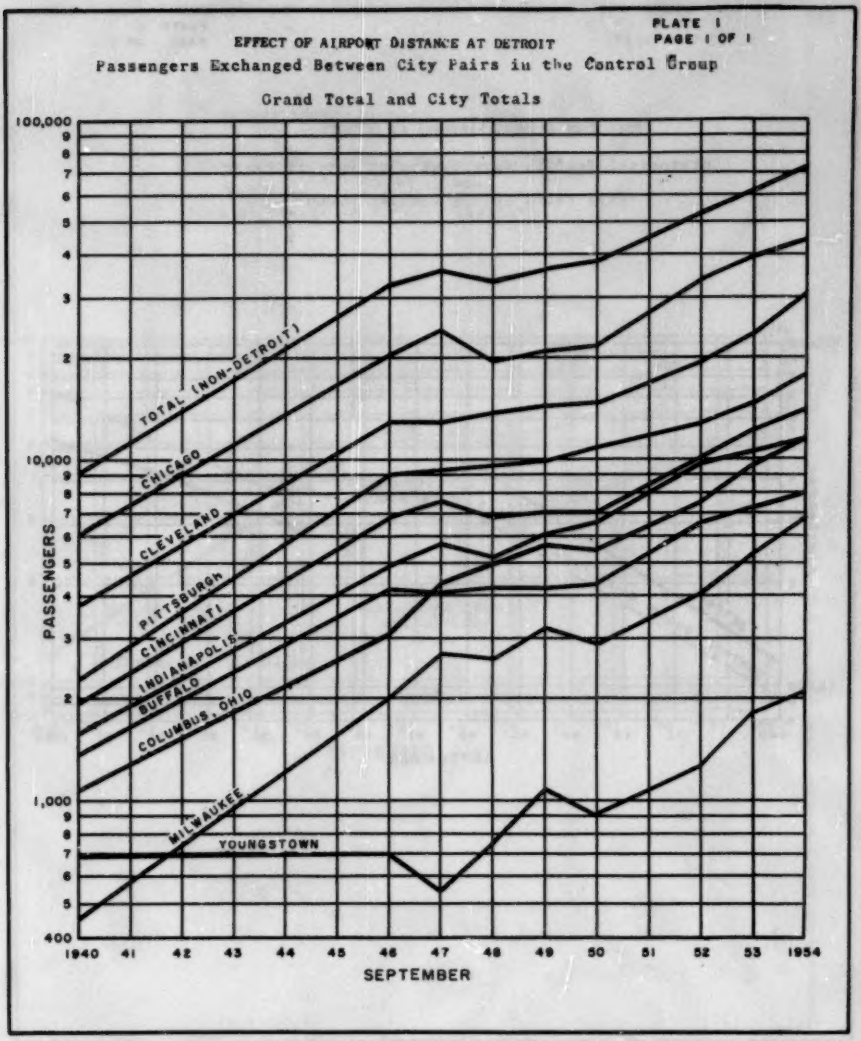

Plate I. Effect of Airport Distance at Detroit - Passengers Exchanged Between City Pairs in the Control Group.

PLATE II
PAGE 1 OF 1

EFFECT OF AIRPORT DISTANCE AT DETROIT

Historical Traffic Development of Detroit Pairs
and
City Pairs in the Control Group

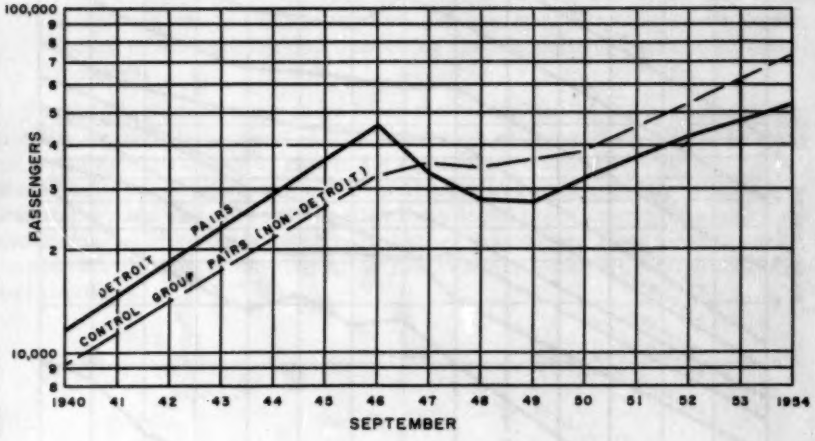

Plate II. Effect of Airport Distance at Detroit - Historical Traffic Development of Detroit Pairs and City Pairs in the Control Group.

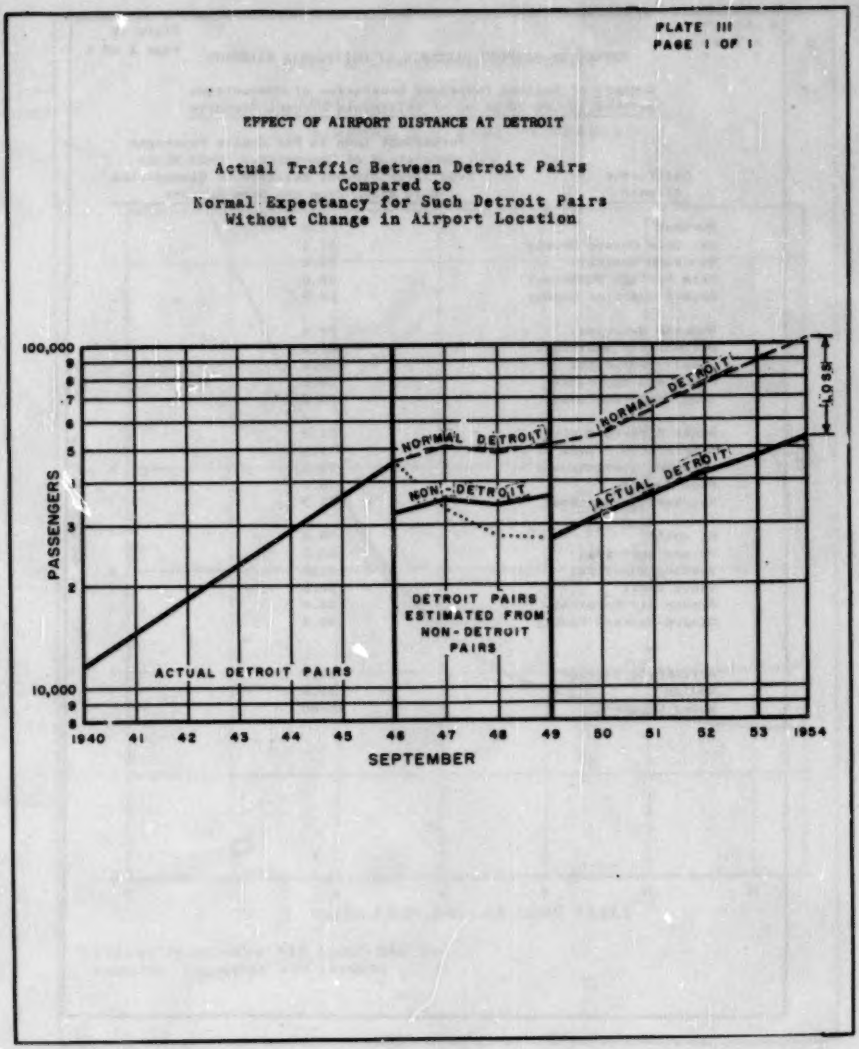

Plate III. Effect of Airport Distance at Detroit - Actual Traffic Between Detroit Pairs Compared to Normal Expectancy for Such Detroit Pairs Without Change in Airport Location.

Plate IV
Page 1 of 1

EFFECT OF AIRPORT DISTANCE AT CALIFORNIA AIRPORTS

Summary of Reduced Passenger Generation of Communities Between 10 and 20 Miles of California Airline Airports

California Airport	Percentage Loss in Per Capita Passenger Generation of Communities 10-20 Miles From Their Airport Relative to Communities 0-10 Miles from the Same Airport
Burbank	7.8
San Luis Obispo County	11.3
Stockton Municipal	43.3
Palm Springs Municipal	48.0
Arcata-Humboldt County	56.9
Modesto Municipal	58.4
Watsonville Municipal	67.6
Visalia Municipal	67.8
San Diego Municipal	68.2
Long Beach Municipal	70.8
Santa Barbara Municipal	71.3
Bakersfield - Kern #1	74.1
Ontario International	74.5
Napa County	75.6
Sacramento Municipal	75.9
El Centro	79.8
Merced Municipal	80.2
Redding Municipal	81.9
Santa Maria	88.5
Fresno Air Terminal	88.8
Oxnard-Ventura County	89.4
Arithmetic Average	65.7
Median	71.3
Modal Group	70-80

Plate IV. Effect of Airport Distance at California Airports - Summary of Reduced Passenger Generation of Communities Between 10 and 20 Miles of California Airports.

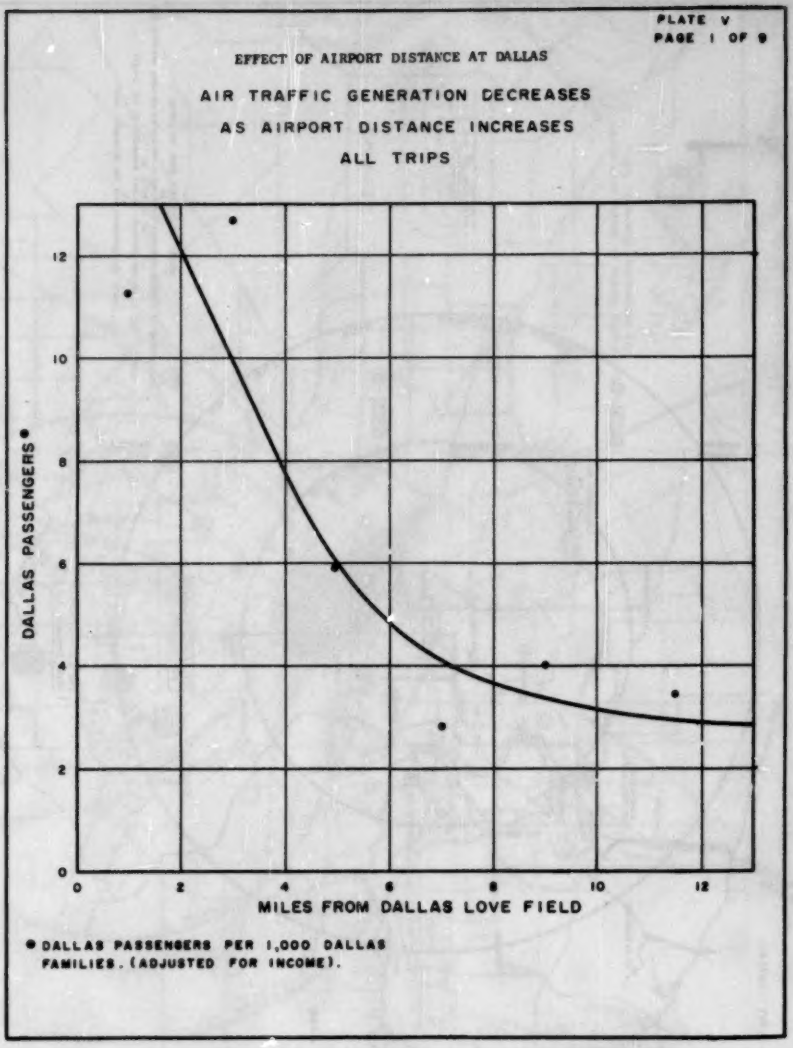

Plate V. Effect of Airport Distance at Dallas.

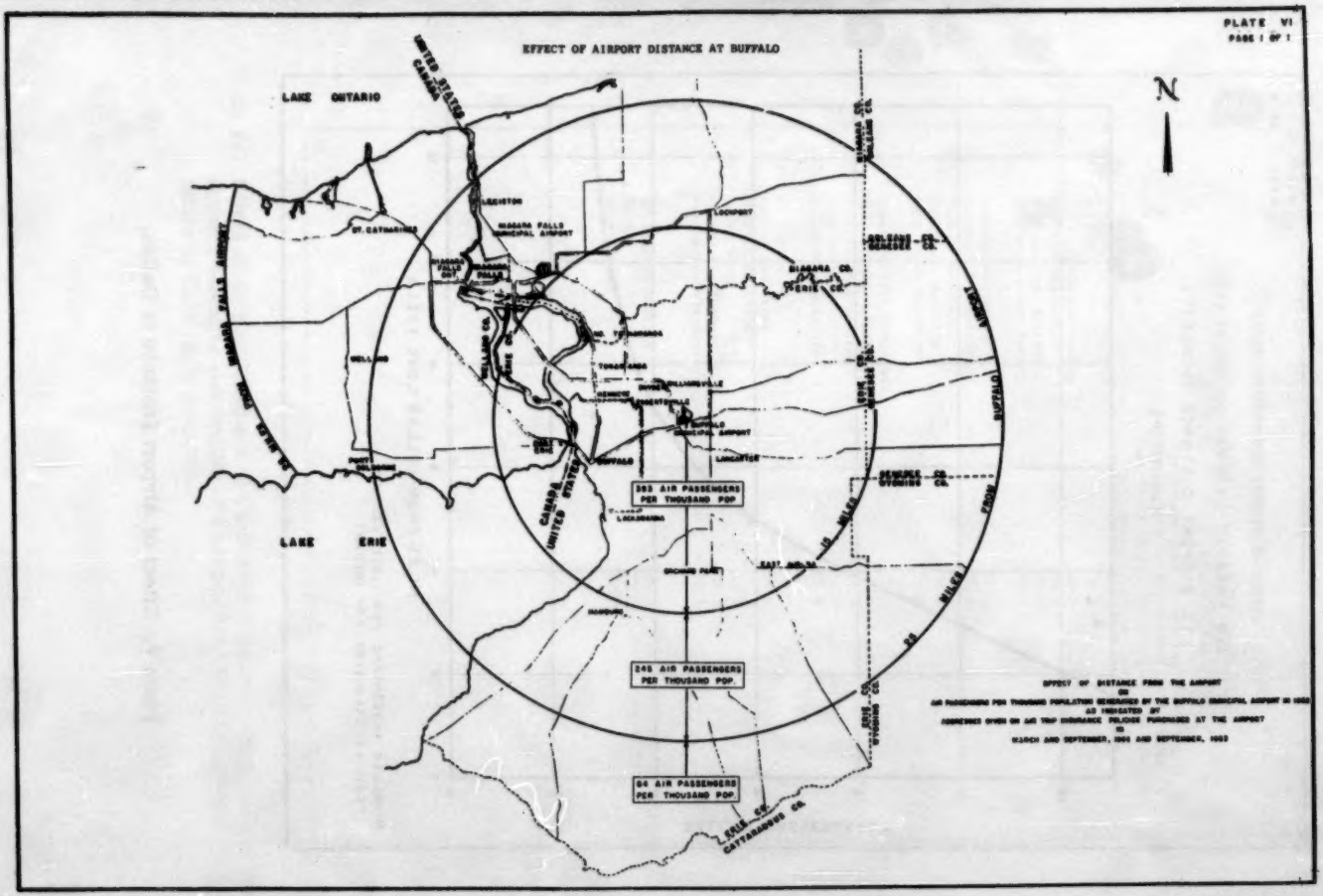
PLATE VI
PAGE 1 OF 1
EFFECT OF AIRPORT DISTANCE AT BUFFALO
LAKE ONTARIO
LAKE ERIE
N
393 AIR PASSENGERS PER THOUSAND POP
245 AIR PASSENGERS PER THOUSAND POP
84 AIR PASSENGERS PER THOUSAND POP
EFFECT OF DISTANCE FROM THE AIRPORT

Plate VI. Effect of Airport Distance at Buffalo.

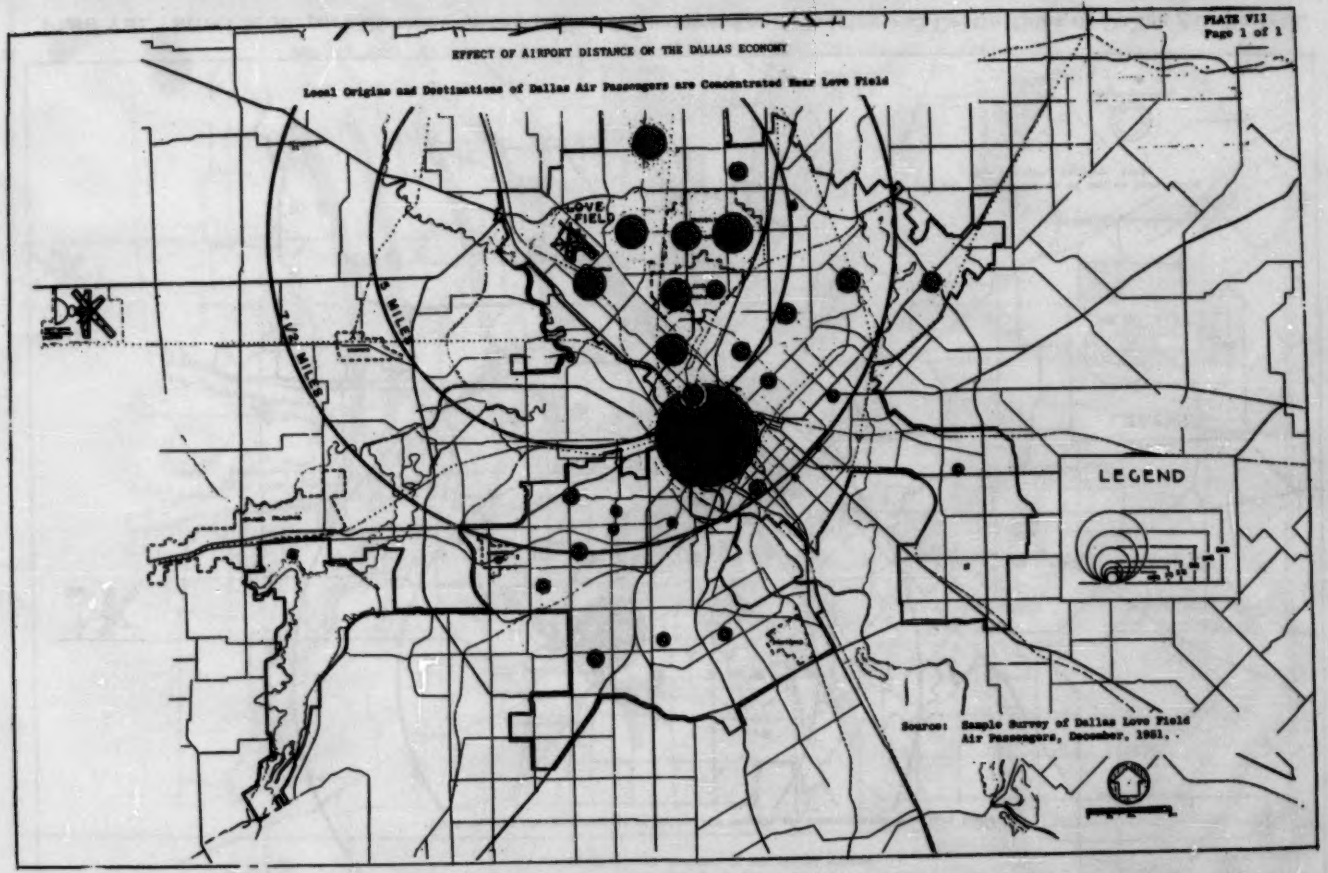
PLATE VII
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EFFECT OF AIRPORT DISTANCE ON THE DALLAS ECONOMY
Local Origins and Destinations of Dallas Air Passengers are Concentrated Near Love Field
LOVE FIELD
5 MILES
7 1/2 MILES
LEGEND
Source: Sample Survey of Dallas Love Field Air Passengers, December, 1961.

Plate VII. Effect of Airport Distance on the Dallas Economy - local Origins and Destinations of Dallas Air Passengers.

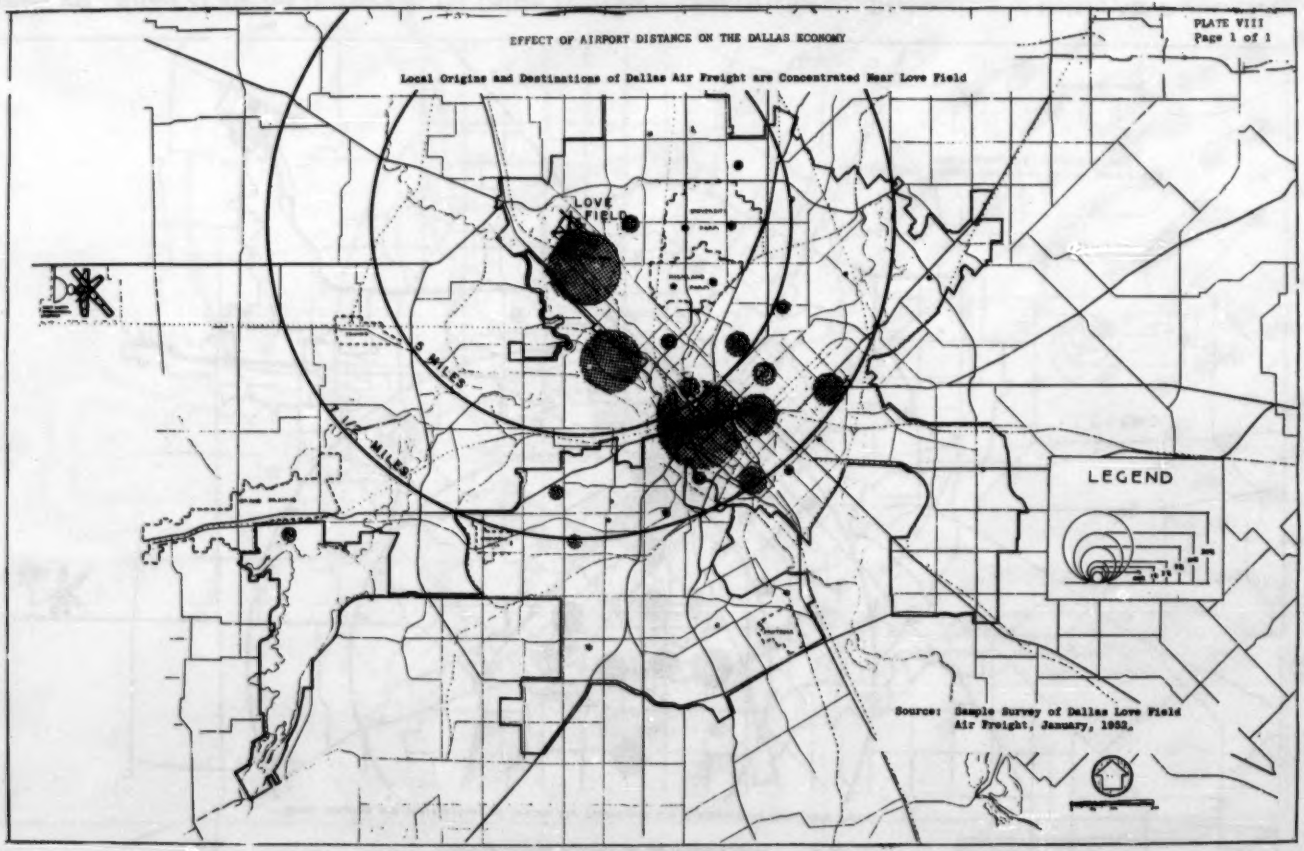
EFFECT OF AIRPORT DISTANCE ON THE DALLAS ECONOMY
PLATE VIII
Page 1 of 1
Local Origins and Destinations of Dallas Air Freight are Concentrated Near Love Field
LOVE FIELD
5 MILES
LEGEND
Source: Sample Survey of Dallas Love Field Air Freight, January, 1952.

Plate VIII. Effect of Airport Distance on the Dallas Economy - Local Origins and Destinations of Dallas Air Freight.

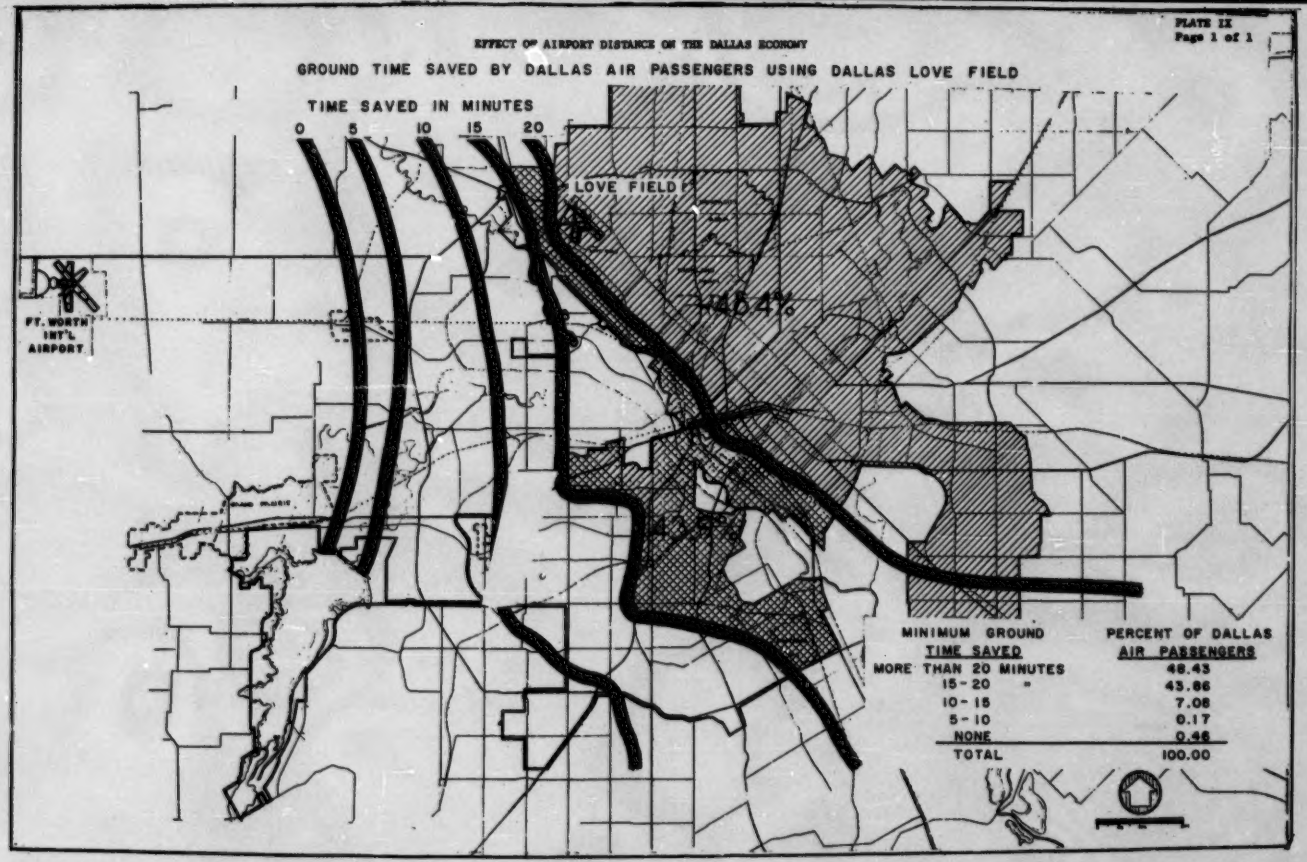
EFFECT OF AIRPORT DISTANCE ON THE DALLAS ECONOMY
PLATE IX
Page 1 of 1
GROUND TIME SAVED BY DALLAS AIR PASSENGERS USING DALLAS LOVE FIELD
TIME SAVED IN MINUTES
0 5 10 15 20
LOVE FIELD
46.4%
FT. WORTH INT'L AIRPORT
MINIMUM GROUND TIME SAVED
PERCENT OF DALLAS AIR PASSENGERS
MORE THAN 20 MINUTES 46.43
15 - 20 " 43.86
10 - 15 7.08
5 - 10 0.17
NONE 0.46
TOTAL 100.00

Plate IX. Effect of Airport Distance on the Dallas Economy - Ground Time Saved by Dallas Passengers Using Dallas Love Field.

Paper 979 AT 2

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THE DESIGN OF NON-RIGID OVERLAYS FOR CONCRETE AIRFIELD PAVEMENTS[a]

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(Proc. Paper 979)

SYNOPSIS

This paper presents in summary form the portion of the U. S. Army, Corps of Engineers Pavement Investigational Program pertaining to the development of design criteria for non-rigid overlays of concrete airfield pavements. Included is a design method which is supported by data from traffic tests of full scale pavements. The step by step development and correlation of these data is given so that the scope, as well as the limitations in the application of the design method, can be understood. The information presented also shows the dominant significance of load repetition in the design of non-rigid overlays on concrete base pavements. The Corps of Engineers practice in the utilization of materials for the construction of non-rigid overlays is summarized briefly.

INTRODUCTION

During World War War II, a large number of military airfields having Portland cement concrete pavements ranging in thickness from 6 to 10 inches were constructed throughout the United States. Pavements of these thicknesses were adequate in the majority of cases for the loadings and traffic produced by aircraft operating during that period. Prior to 1944, a period in which the majority of these relatively thin pavements were designed and constructed, the most severe loadings imposed upon military airfields were those of the B-17 and B-24 bomber aircraft. Main gear loads were in the range of

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30,000 to 40,000 pounds on single wheels with tire inflation pressures of approximately 100 psi.

By 1945 it was apparent that greater airfield pavement thicknesses would be needed to support the B-29 aircraft and other heavier planes still on the drawing board or in the development stage. The Corps of Engineers Rigid Pavement Laboratory, Cincinnati, Ohio and Flexible Pavement Laboratory, Waterways Experiment Station, Vicksburg, Mississippi initiated accelerated traffic test programs on test sections of pavement at Lockbourne Air Force Base, Ohio and Vicksburg, Mississippi. From the results of these programs, new airfield pavement design criteria were established in 1947 for heavy multiple wheel, high tire inflation pressure landing gears, such as the 100,000 pound twin wheel load of the B-47 and the 200,000 pound twin tandem gear load of the B-36. Although the 1947 design procedure solved the immediate problem of design for new construction, it was recognized that criteria for reinforcing the older concrete pavements to provide adequate load carrying capacity would also be required. Tests at Lockbourne had already provided a design procedure for the rigid overlay of a rigid base pavement, but very little test data were available for the problem of overlaying rigid pavements with non-rigid or flexible pavement materials.

The Test Program

As with the formulation of design procedures for rigid and flexible pavements for unprecedented aircraft gear loadings and operational characteristics, the Corps of Engineers has placed great reliance on accelerated traffic tests of specially constructed overlay pavement test sections for gaining design information. These tests for overlay pavements were started in 1945 and have continued to the present time. More recently, with the increase in magnitude and frequency of highway vehicle loads, highway engineers have resorted to this type of pavement evaluation. Several examples of this type of testing for highways are the Maryland road tests, the WASHO road tests in Idaho, and the presently proposed Illinois test roads. This method of testing for the various types of airfield pavements is well covered in the technical literature of the Highway Research Board, the American Society of Civil Engineers, and numerous published reports of the Corps of Engineers organizations carrying on such tests (1, 2, 3, 4). An overall summary of the complete investigational program pertaining to rigid pavements and overlays of rigid pavements is given in reference (8).

This paper deals more specifically with the results of the accelerated traffic tests conducted by the Corps of Engineers on six overlay test tracks. The pertinent characteristics of these test tracks are summarized in Table 1. From this tabulation it can be noted that traffic loadings ranged from a 25,000 lb. single wheel load on high pressure tires to 100,000 lbs. on twin wheels with high pressure tires. Also, concrete base pavement thicknesses ranged from 6 to 12 inches, with flexible and asphaltic concrete overlay thicknesses varying from 3 to 42 inches. This includes a total of 53 test items.

Table 2 presents a more detailed summary of the physical characteristics of the individual test items. The first three columns, which are given to identification, are self-explanatory. In the columns which follow, "h" is the thickness of the concrete base pavement, "t" is the thickness of the non-rigid overlay, "R" is the flexural strength of the concrete base pavement, "k" is

the modulus of subgrade reaction, and "h_d" is the full design thickness of Portland cement concrete required for the traffic loading. Column 9 gives the number of traffic coverages at which the overlay failed. One coverage can be defined as one maximum stress repetition produced at each point in the pavement by planned routing of the loading rig. (The number of coverages used in the design of a pavement is based on the volume of traffic by the operation of military aircraft expected on that pavement in a definite period, generally in excess of ten years.) The remaining columns comprise an integral part of the analysis and will be discussed later.

In analyzing data from several of the early test projects (1945 to 1951), many performance observations and conclusions were made during testing which, in retrospect, apply only to the conditions present in those particular test sections. Early design criteria for flexible overlays, while approximately correct for high strength foundations, proved to be critically unconservative for low strength subgrades. The defects in the early design criteria can be traced directly to lack of test data on low strength subgrade in the tests at Maxwell and MacDill Fields, as the results from these tests were representative of pavements on relatively high strength subgrades only. Subsequent testing has shown that the required overlay thickness is particularly sensitive to the strength of the subgrade. Tests at Lockbourne and Sharonville No. 1 were conducted on subgrades which ranged in strength from low to medium. While the results of these tests tended to reveal the inconsistencies in the early criteria, the interim changes in the criteria were cumbersome and did not explain adequately the performance of all test sections. With these factors in mind, the Sharonville Overlay Test Track No. 2 was deliberately designed and constructed on a uniform, low strength, high plastic clay subgrade. Upon the conclusion of traffic tests on the latter track, a re-examination of all previous test results was made. This study led to the formulation of a non-rigid overlay design concept which accurately explained the performance of all test sections and was consistent with observations made at prototype airfields subjected to several years of aircraft operation.

Traffic Test Procedures

Figure 1 shows the plan and sections of the Sharonville Overlay Test Track No. 2. It can be noted that this plan makes provision for two test lanes with areas at each end for maneuvering the traffic loading equipment. Also included in this plan are several Portland cement concrete overlays which do not fall within the scope of the present paper. Details of procedural control during the accelerated traffic testing of these sections may be found in references (1), (2), and (3). Briefly, the information obtained from these tests falls in two categories, the performance observations, and numerical data. Both of these types of information are related to the magnitude and frequency of the loading and the physical properties of the pavement components. The numerical data included dynamic and permanent deflections of the base pavement and overlay, dynamic strain measurements at critical points in the base pavement, and shear strains and pressure distribution at the interface between the overlay and base pavement. Such measurements are designed to provide a basis for a purely theoretical analysis of the results and have proved quite successful in this respect for plain Portland cement concrete pavements. At the present time, however, because of the complicated structure of the

overlay pavements, more reliance and ultimately the weight of the analysis has been placed on the empirical data obtained from the performance observations. The more important of these performance observations included determinations of the permanent deformation and general condition of the overlay surface and concrete base pavement at three stages during the traffic life. These were (1) prior to failure of the overlay; (2) at incipient failure of the overlay; (3) following the complete breakup of the overlay surface.

To illustrate better the various performance characteristics, specific examples have been selected from the results of the tests at the Sharonville Overlay Test Tracks. Figure 2 shows two views of the load rig used to apply traffic. The twin wheels carrying the 100,000 lb. load box are shown in the lower photograph. These wheels are spaced 37-inches center to center and each tire has a contact area of 267 square inches.

Figure 3 shows a typical "after traffic" test cut made through a failed asphaltic concrete overlay to observe the general condition of the base pavement after overlay failure.

Figure 4 shows typical overlay surface and base pavement conditions for three cases:

(a) Traffic continued after failure.
(b) Traffic halted at first signs of failure.
(c) Traffic insufficient to cause failure.

Figure 5 is a typical plotting of the cumulative permanent and dynamic deflections occurring in the base pavement during the service life of the overlay. These measurements were taken with an electric deflection gage located near the corner of a slab in the concrete base pavement.

The failure of a non-rigid overlay test item is determined by visual observation of the pavement surface. In the Sharonville overlay tests, large dynamic deflections and pavement displacements (Figures 3 and 4) occurred rapidly after the first signs of visible transient deflection. Hence, failure was generally established at the number of traffic coverages corresponding to the first signs of visible deflection. It is significant that all deflection plots, similar to those shown in Figure 5, indicated an increasing rate of transient and permanent deflection in the concrete base pavement at a number of coverages uniformly consistent with the number previously established by the visible deflection criterion.

A Basis for Design

In formulating a logical approach to establishing the non-rigid overlay design criteria, one factor which had not been considered previously was found to be of particular importance. This factor was the degree to which the concrete base pavement is broken or cracked at the time of failure. The results of the tests at the two Sharonville Overlay Test Tracks indicated that the base pavement begins to break soon after traffic is applied and continues to break until the average size of the integral pieces is from 5 to 7 square feet in area, with no apparent effect on the overlay surface. Traffic beyond this point causes continued cracking of the base pavement, a definite increase in dynamic or transient deflections, and ultimately shear failure in the foundation. Pursuing this line of reasoning, it would seem that, during the life span of a flexible overlay pavement, the concrete base pavement passes initially from a

rigid condition to a semi-rigid condition during service and finally to a flexible condition at failure. From this it can be inferred that if sufficient high quality flexible overlay is placed upon a base pavement to prevent its cracking into pieces of critically small size during the desired pavement life, adequate performance will be insured. In order to make practical use of this observation, it was necessary to establish the relationship between the rate of concrete pavement breakup under traffic loading and the physical properties of the concrete and subgrade.

It was realized that the dimensions of a piece of base pavement under a given loading which would cause shear failure of the subgrade would necessarily vary with the shear strength of the subgrade. However, for the Lockbourne and Sharonville Overlay Test Tracks, where a general range of subgrade modulus values from 50 to 150 lbs/in^3 was encountered, the degree of cracking at failure was essentially constant. That is, the average size of the pieces of base pavement in all items which were trafficked beyond failure was smaller than the 5 to 7 square foot range (Figure 4a). The items which did not fail exhibited base slab pieces larger than that range (Figure 4c). On the few test items where traffic was halted and the flexible overlay removed just prior to or at incipient failure, the average size piece of base pavement was uniformly within the 5 to 7 square foot range (Figure 4b).

If a greater degree of cracking can be allowed for higher strength subgrades, then the new design procedure will tend to be slightly conservative for those conditions. An analysis of the results of the various overlay investigations also indicated that the subgrade modulus, "k," gives an adequate index of the quality of the pavement foundation and that other strength determinations, such as the CBR, would be an unnecessary duplication.

Correlation

Three pertinent items of information which have been developed and provide a cue for a semi-empirical correlation of the performance data are:

1) Considerable breakup of the concrete base pavement can occur before failure of the overlay takes place.
2) The base pavement will be reduced to pieces 5 to 7 square feet in area just prior to failure of the overlay.
3) The rate of breakup of the concrete base slab decreases as the value of "k," the subgrade modulus, increases.

These findings were correlated with information available on the rate of breakup of plain concrete pavements under various degrees of overload. The bulk of the information on plain concrete pavements was obtained from test results of the Lockbourne No. 1 Test Track.[1, 4] From this data the curves of Figure 6 were derived. These curves define "complete failure" for a plain concrete pavement by showing the number of coverages with respect to percent of design thickness that will cause a pavement slab to break up into pieces about 7 square feet in area. The rate of failure is much slower for high "k" values than for low "k" values. For example, on Figure 6 at a "k" value of 300 lbs/in^3, 56 percent of the design thickness is required to carry 1000 traffic coverages before the pavement slabs break up into pieces about 7 square feet in area (complete failure); while at a "k" value of 100 lbs/in^3, 77 percent of the design thickness is required for the 1000 coverages. Another

means of reducing this rate of breakup is to place an overlay (non-rigid) over the concrete base pavement. Therefore, there should be a means of relating the performance of the base slab with the overlay on it to an equivalent thickness of plain concrete pavement that would perform in the same manner under traffic loading. This can be done with the information available in Table 2 and Figure 6 as follows. For example, Item No. 11 on Table 2, a 5.6 inch A. C. overlay on a 6-inch concrete base pavement failed at 70 coverages of the traffic loading. The full design thickness of concrete, h_d, required for this loading and a subgrade modulus of 100 lbs/in^3 is 16.0 inches. Going to Figure 6, it is indicated that for a "k" value of 100 lbs/in^3, 51 percent of the design thickness, h_d, is required in order that by the end of 70 coverages a plain concrete slab will be broken into pieces 7 square feet in area. The thickness, h_d', of this hypothetical slab should then be 0.51 x 16.0, or 8.2 inches. Subtracting from this thickness, h_d', (8.2 inches) the actual thickness of the base slab, h, (6.0 inches) yields 2.2 inches, which is called the "concrete deficiency." This value is given in the last column of Table 2 for every item listed. For every overlay thickness there is a value of concrete deficiency that reflects with reasonable accuracy satisfactory performance of the overlay up to the time of failure at a specific number of coverages.

Figure 7 is a plot of the overlay thickness, t, versus the concrete deficiency, (h_d' - h), each point being labeled with its corresponding test item number. Considering the variables that enter into such a plot (concrete strength, design thickness determination, subgrade modulus, coverages at failure, etc.), the results are remarkably consistent. It should be noted that there is little difference between the various types of overlay, the overlays incorporating a high quality base course material having performed as well as comparable thicknesses of full asphaltic concrete. A "design" line, which is on the conservative boundary of the points plotted, has been placed on Figure 7. In fact, the "design" line, which shows a 2.5 to 1 ratio between flexible overlay thickness and concrete deficiency, encompasses all items that were carried to failure; and only those items which were not failed under the imposed traffic fall below this recommended design slope. For these unfailed items, the indication is that less overlay thickness would have carried the same number of coverages.

Overlay Design Procedure

At the time of preparation of Table 2 and Figure 6, all concrete airfield pavement thicknesses were computed from Corps of Engineers design curves,[5] which are based on Westergaard's formulas for stress at a free edge.[7] The test results from plain concrete pavement test tracks at Lockbourne had imposed certain empirical adjustments to Westergaard's formulas, such as factors for load transfer at a joint and for safety or "fatigue" to insure adequate thickness for 5000 traffic coverages. This level of traffic was considered equivalent to that which would be imposed on a prototype airfield in a period of from 10 to 20 years. Recent changes in aircraft operational characteristics and gear configurations have caused the aircraft to produce coverages on a taxiway at a more rapid rate than on runways or aprons. This is due primarily to a greater channelization within a narrow width of pavement for operation on a taxiway. Consequently, the Corps of Engineers concrete pavement design curves have been modified recently to

give an increased pavement thickness, based upon 30,000 traffic coverages, plus an additional safety factor, in channelized areas. Design curves for non-channelized areas, such as aprons and runways, have remained the same. Examples of two of the Corps of Engineers concrete pavement design curves are presented in Figures 9 and 10.

To determine the required thickness of non-rigid overlay for increasing the load carrying capacity of an existing concrete pavement, first compute the full rigid pavement design thickness, h_d, required for the new design loading. The previously mentioned rigid pavement design curves similar to those in Figures 9 and 10 are used in this computation. The curves are entered with the new design loading, the flexural strength of the existing concrete base pavement, and the existing subgrade modulus, "k," beneath the base pavement.

Second, compute the "complete failure" single slab thickness, h_d', which is the factor F, obtained from Figure 8, times the previously determined full concrete design thickness, h_d.

$$h_d' = F\, h_d \qquad (1)$$

The curve for non-channelized areas in Figure 8 is a direct extraction from Figure 6 of percentages for various "k" values at 5000 coverages. The curve for channelized areas is based on similar values from Figure 6 at 30,000 coverages. The latter curve has been adjusted to compensate for the increased thickness requirements that have been effected recently in rigid pavement design for channelized areas.

In view of the fact that the "design" line in Figure 7 is a straight line, the required non-rigid overlay thickness, t, can be computed by the formula:

$$t = 2.5\,(h_d' - h) \qquad (2)$$

where: t = non-rigid overlay thickness.

h_d' = "complete failure" single slab thickness.

h = existing concrete pavement thickness.

Substituting Eq. 1 in Eq. 2 gives the following as the thickness of non-rigid overlay required:

$$t = 2.5\,(F\, h_d - h) \qquad (3)$$

Utilization of Overlay Materials

As previously indicated, little difference was noted between overlays incorporating a high quality base course material and those composed of asphaltic concrete for the full depth of overlay. The Corps of Engineers has discontinued the use of a plant mix "black base" asphaltic concrete in non-rigid overlays and will permit only asphaltic concrete meeting the binder and surface course requirements. This practice was adopted primarily because of difficulty in obtaining the desired uniformity, density, and stability of the "black base" product in field construction, not because of any inherent load distributing deficiency of material. With regard to materials for the "high quality base course," only those meeting the requirements for water-bound macadam and well graded crushed stone base courses as set forth in Corps of Engineers Guide Specifications are considered acceptable.

The following paragraphs present some basic considerations to aid the designer in the determination of non-rigid overlay types:

Minimum Thickness: In order to reduce the possibility of the base pavement crack and joint patterns reflecting through the overlay, a minimum overlay requirement of 4 inches of asphaltic concrete is recommended in all cases. This minimum has been established from observations at a large number of airfields. The 4 inch value should be used as a minimum requirement only, and where local experience indicates that greater thicknesses are necessary for the prevention of reflection cracking, this value should be increased accordingly.

Selection of Overlay Types: The thickness of asphaltic concrete pavement to be used as the top portion of an overlay incorporating a base course material should be consistent with requirements set forth in the Corps of Engineers Flexible Pavement Design Manual.(6) These thickness requirements are summarized, in part, in Table 3.

Less than 4 inches of base course materials should never be incorporated in an overlay. The required thickness of asphaltic concrete to be placed over a high quality base course material will determine generally whether a full asphaltic concrete overlay is required or at what overlay thickness a base course material may be used. Thus, for a design load of 25,000 pounds on a single wheel having a tire pressure of 200 psi, full asphaltic concrete overlays would be required for thicknesses up to 6 inches, while high quality base course material could be used for overlay thicknesses of 7 inches or greater.

Discussion

Another method of designing non-rigid overlays for concrete base pavements is to consider the concrete base as a high quality base course and follow the flexible pavement design procedure of the Corps of Engineers.(6) Table 4 shows a comparison of this method with the overlay design procedure outlined in the preceding portion of this paper. The overlay thicknesses given in the last four columns of this table are for taxiways. The concrete flexural strength used for the base pavement is 650 lbs/in^2. For the lower values of subgrade modulus, "k," in the range of 75 to 200 lbs/in^3, there is a considerable saving in overlay thickness by the overlay design procedure. For the higher values of "k," the flexible pavement design procedure and the overlay design procedure are more or less comparable. Both methods are used by the Corps, the one giving the lesser thickness being given preference.

On Figure 6 it can be noted that the curves have been extended from about 5000 coverages to 30,000 coverages on the basis of data which is limited to between 100 and 5000 coverages. Also, the overlay performance data given in Table 2 fall within this range. Recently some of the items of the Sharonville Overlay Test Track No. 2 have been trafficked in the 5000 to 20,000 coverage range. Performance predictions in this range on the basis of Figures 6 and 7 have proved quite acceptable and have been on the conservative side. At the present time full scale traffic tests for plain concrete and overlay test sections are under way to establish better the performance characteristics of these pavements up to 30,000 coverages.

The effect on overlay thickness of steel reinforcement in the concrete base pavement is not subject to specific consideration at this time. However, it has been established that the use of reinforcement in concrete pavements in

nominal amounts will materially retard the rate at which an overloaded pavement will break up.(9) Therefore, in the design of non-rigid overlays, this factor, which might result in lesser thickness requirements, should be considered. The current investigational program of the Corps of Engineers is placing considerable emphasis on the use of continuous reinforcement for concrete airfield pavements, and information which can be correlated with overlay design procedures should be available within the next six months.

The method of analysis and the data here presented provide a ready means of evaluating non-rigid overlay pavements already in operation at airfields. For example, if the physical properties of the pavement components and the thicknesses of the base pavement and overlay are known, the number of coverages of any aircraft loading that the pavement will carry without failure can be determined, using the information on Figures 6 and 7. For evaluation purposes it must also be known how many operations (a landing and takeoff) will produce one coverage. This will be controlled by traffic on the main taxiways, since it is the most concentrated and channelized on these features. To illustrate, two operations of a B-47 heavy bomber produce approximately one coverage on a primary taxiway, while ten to twelve operations are required to produce one coverage on a runway.

CONCLUSIONS

The following conclusions will serve to summarize the information presented and discussed in this paper:

1) The analysis of the structural behavior of non-rigid overlays under repeated traffic loadings is very complex and has, as yet, depended on a primarily empirical approach rather than an entirely theoretical one.

2) The method of design developed for non-rigid overlays is primarily empirical and is based on the correlation of results obtained from full scale traffic tests.

3) Full scale traffic tests provide an excellent means of obtaining design information for airfield pavements.

4) Full scale traffic test operations must take into consideration the gear configurations, gear loadings, and operational characteristics of both current aircraft and those that can be foreseen in the future.

5) Full scale traffic tests are most valuable where a large variety of conditions have been incorporated in the pavements and their support.

6) Non-rigid overlays will perform satisfactorily after considerable breakup or cracking has occurred in the rigid base pavement.

7) The rate of breakup of the concrete base slab beneath a non-rigid overlay is very dependent on the subgrade modulus or the amount of subgrade support. This is also true for overloaded plain concrete pavements.

8) The design of a non-rigid overlay must be related not only to the magnitude of the gear load but also to the number and frequency of load repetitions that will occur on the pavement during its design life.

9) There is no great difference between overlays incorporating high quality base course materials and those constructed of asphaltic concrete for their full depth.

10) When steel reinforcement is present in the concrete base pavement, there is every indication that the non-rigid overlay thickness for a given design loading will be less than that required for a plain concrete base pavement.

11) The information and design procedures presented herein provide a good basis for evaluating the expected service life of a non-rigid overlay under any magnitude of gear load and frequency of aircraft operation.

ACKNOWLEDGMENTS

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Table 1

Summary of Corps of Engineers Non-Rigid Overlay Test Sections

Project	Range of Pavement Thickness		Test Landing Gear Configuration
	Base Pavement (Inches)	Overlay (Inches)	
MacDill Field, Fla. (1945 - 1946, High Strength Subgrade)	6	3 to 9 (4 Items)	60,000 Lb. Twin Wheels, Low Tire Pressure.
Maxwell Field, Ala. (1945 - 1946, High Strength Subgrade)	6	3 to 12 (4 Items)	60,000 Lb. Twin Wheels, Low Tire Pressure.
Lockbourne No. 3 (1947-1949, Low to Medium Strength Subgrade)	6	3 to 12 (8 Items)	60,000 Lb. Twin Wheels, Low Tire Pressure.
Sharonville No. 1 (1951 - 1953, Low to Medium Strength Subgrade)	6 - 10	3 to 24 (16 Items)	100,000 Lb. Twin Wheels, High Tire Pressure.
Sharonville No. 2 (1953 - 1955, Low Strength Subgrade)	6 - 12	3 to 42 (16 Items)	100,000 Lb. Twin Wheels, High Tire Pressure.
Sharonville No. 3 (1953, Shattered Base Pavement)	6	3 to 7 (5 Items)	25,000 Lb. Single Wheel, High Tire Pressure.

TABLE NO. 2

SUMMARY OF TEST RESULTS, NON-RIGID OVERLAY TEST SECTIONS: SHARONVILLE NO. 1 AND NO. 2

TEST SECTION IDENTIFICATION	NON-RIGID OVERLAY TYPE	ITEM NO.	h INCHES	t INCHES	R PSI	K LBS/IN^3	h_d INCHES	COVERAGES AT FAILURE	COMPLETE FAILURE THICKNESS		CONCRETE DEFICIENCY	REMARKS
									h_d' % h_d	h_d' INCHES	$h_d' - h$ INCHES	
Sharonville No. 1	All A.C. (Binder & Surface)	11	6.0	5.6	725	100	16.0	70	51	8.2	2.2	
	"	14	6.5	3.4	680	100	16.6	60	49	8.1	1.6	
	"	13	8.0	2.9	680	90	16.9	70	54	9.1	1.1	
	"	16	8.1	3.0	620	300	15.6	1410	60	9.4	1.3	
	"	10	9.5	6.4	725	150	15.4	3000/	85	13.1	3.6	
	"	12	9.5	2.9	725	125	15.7	1150	75	11.8	2.3	
	"	15	9.6	3.0	680	160	16.0	1200	73	11.7	2.1	
Sharonville No. 1	Black Base (Plant Mix), 1"A.C. Surface	8	5.5	9.8	725	75	16.4	130	63.5	10.4	4.9	
	"	5	5.6	13.2	670	60	17.5	200	71	12.4	6.8	
	"	4	5.7	15.8	640	65	17.9	250	72	12.9	7.2	
	"	9	7.7	8.2	725	100	16.0	485	70	11.2	3.5	
	"	6	8.0	12.2	670	50	17.8	270	76.5	13.6	5.6	
	"	7	9.6	10.3	670	60	17.5	1250	85	14.9	5.3	
Sharonville No. 1	W. B. Macadam, 1"A.C. Surface	1	5.1	12.1	640	75	17.7	130	63	11.3	6.2	
	"	2	5.8	18.0	640	85	17.5	950	78	13.7	7.9	
	"	3	5.6	24.5	640	100	17.2	3000/	88	15.2	9.6	
Sharonville No. 2	All A.C. (Binder & Surface)	34	5.75	9.5	675	65	17.2	90	63	10.8	5.0	
	"	32	5.75	14.5	800	65	15.4	1280	84	12.95	7.2	
	"	31	5.75	20.5	800	65	15.4	4000	92	14.35	8.6	
	"	38	7.75	6.0	750	65	16.2	170	69	11.2	3.4	
	"	36	7.75	9.5	650	65	17.5	215	70	12.25	4.5	
	"	33	7.75	11.5	800	65	15.4	1700	86.5	13.3	5.8	
	"	39	9.75	4.25	825	65	15.0	690	80	12.0	2.2	
	"	37	9.75	7.0	650	65	17.5	425	76	13.3	3.5	
	"	35	9.75	9.5	650	65	17.5	950	82	14.35	4.6	
	"	40	11.75	4.0	825	65	15.0	4620	93	13.95	2.2	
	"	41	11.75	3.0	825	65	15.0	2130	88	13.2	1.5	
Sharonville No. 2	Stabilized Crushed Rock, 1"A.C. Surface	29	5.75	42.0	775	65	15.9	3000/	95/	15.1	9.3	
	"	17	5.75	35.0	775	65	15.9	3000/	95/	15.1	9.3	
	"	30	7.75	23.0	775	65	15.9	3000/	95/	15.1	7.3	
	"	18	7.75	17.0	775	65	15.9	*6500	95	15.1	7.3	*11,000 coverages were applied. Surface cracking became severe at 6500 coverages.
	"	19	7.75	12.5	775	65	15.9	1135	83	13.2	5.4	
	"	20	9.75	9.0	775	50	16.1	1000	85.5	13.75	4.0	

TABLE NO. 2 (CONT'D)

SUMMARY OF TEST RESULTS, NON-RIGID OVERLAY TEST SECTIONS: MAXWELL, MACDILL, AND LOCKBOURNE NO. 3

TEST SECTION IDENTIFICATION	NON-RIGID OVERLAY TYPE	ITEM NO.	h INCHES	t INCHES	R PSI	K LBS/IN^3	h_d INCHES	COVERAGES AT FAILURE	COMPLETE FAILURE THICKNESS h_d' % h_d	COMPLETE FAILURE THICKNESS h_d' INCHES	CONCRETE DEFICIENCY $h_d' - h$ INCHES	REMARKS
Maxwell	All A.C.	A	6	6	655	*260	10.7	3000/	72/	7.7	1.7	*K values corrected for plate bending
	"	B	6	3	614	260	11.2	3000/	72/	8.1	2.1	
	"	C	6	4	645	260	10.8	3000/	72/	7.8	1.8	
MacDill	All A.C.	1	6	3	665	*370	10.3	3000/	58/	6.0	**No Deficiency	**-"No Concrete Deficiency" means the 6" base pavement could carry 3000 coverages of the test loading without an overlay. The pavement would crack but not to the degree necessary for shear failure in the subgrade.
	"	2	6	3	665	370	10.3	3000/	58/	6.0	"	
	"	3	6	5	840	370	8.6	3000/	58/	5.0	"	
	"	5	6	7	840	370	8.6	3000/	58/	5.0	"	
Lockbourne No. 3	All A.C. (Binder & Surface)	2C, 2K	6	3	900	270	8.2	3000/	71/	5.8	No Deficiency	
Lockbourne No. 3	Black Base, 3" A.C. Surface	3C, 3K	6	6	900	75	9.8	3000/	89/	8.7	2.7	
Lockbourne No. 3	Sand Asphalt Base 3" A.C. Surface	5C, 5K	6	9	900	75	9.8	3000/	89/	8.7	2.7	
Lockbourne No. 3	Black Base 3" A.C. Surface	7C, 7K	6	9	900	75	9.8	3000/	89/	8.7	2.7	

h = Thickness of Portland Cement Concrete Base Pavement
t = Thickness of Non-Rigid Overlay
R = Flexural Strength of Concrete Base Pavement
K = Modulus of Subgrade Reaction
h_d = Full Concrete Design Thickness for Test Loading (5000 Coverages)
h_d' = "Complete Failure" Concrete Thickness (Coverages at Failure)

Table 3

Summary of Corps of Engineers
A.C. Requirements for Non-Rigid Overlays

Wheel Assembly	Tire Pressure (psi)	Load On Assembly (Pounds)	Minimum Thickness of A.C. Pavement (Inches)
Single	100	< 30,000	2
		> 30,000	3
	200	< 30,000	3
		> 30,000	4
Twin (37.5 - Inch Spacing)	See Note	< 45,000	2
		45,000 - 60,000	3
		> 60,000	4

NOTE: Tires on twin wheel assemblies are maintained at a constant contact area of 267 square inches by varying the tire-inflation pressure with variations in assembly load.

Table 4

Comparison of Flexible Pavement and Overlay
Design Procedures for 100,000 Lb. Twin Wheel Load

Subgrade Modulus "k" (lbs/in^3)	Corresponding CBR (Percent)	Taxiway Overlay Thickness "t" (Inches)			
		6-Inch Concrete Base		8-Inch Concrete Base	
		Overlay Procedure	Flexible Pavement Procedure	Overlay Procedure	Pavement Procedure
75	3	32	117	27	115
200	10	24	29	19	27
400	40	9	7	4	5

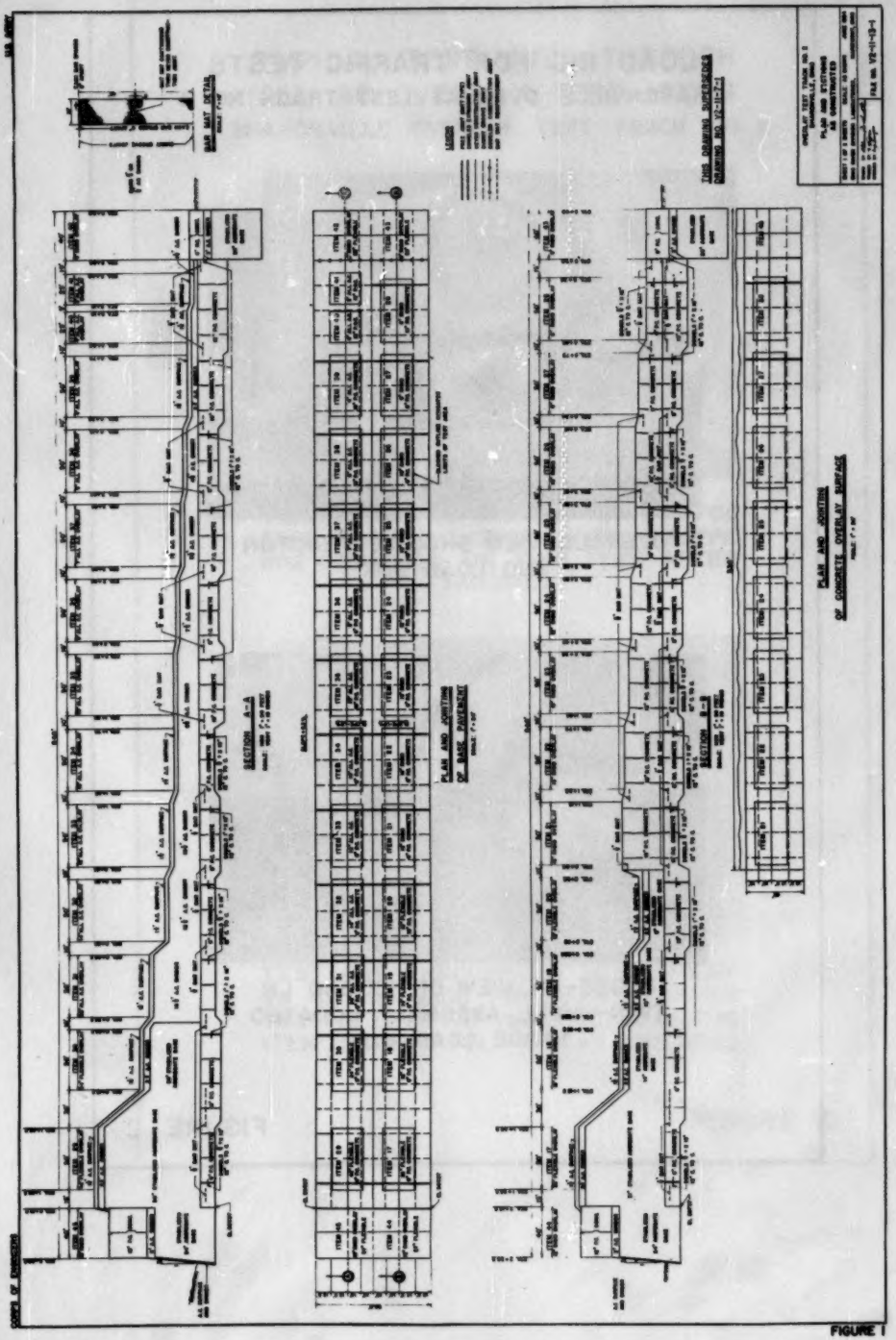
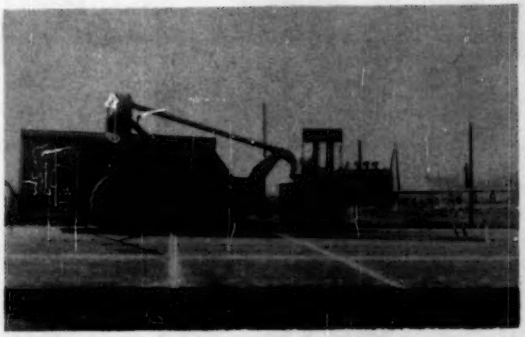


FIGURE 1

LOAD RIG FOR TRAFFIC TESTS
SHARONVILLE OVERLAY TEST TRACK NO. 2

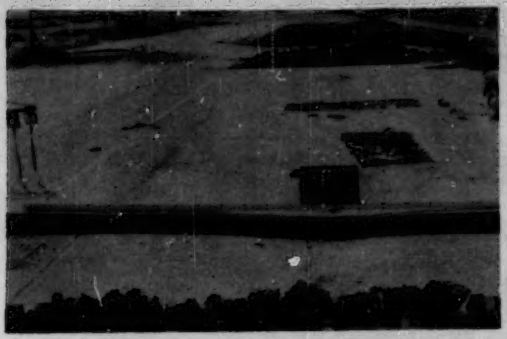


OVERALL VIEW SHOWING TRACTOR AND LOAD BOX

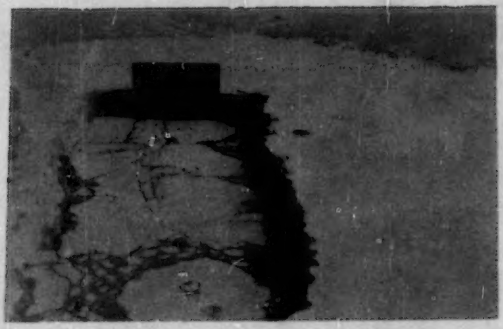
CLOSE-UP VIEW OF 100,000 LB. TWIN-WHEEL ASSEMBLY LOCATED INSIDE LOAD BOX

FIGURE 2

TYPICAL TEST CUTS THROUGH ALL AC OVERLAY TEST ITEMS
SHARONVILLE OVERLAY TEST TRACK NO. 2



VIEW OF 9.5" AC OVERLAY ON 8" PCC BASE PAVEMENT AFTER TRAFFIC (TRAFFIC WAS CONTINUED ON THIS ITEM AFTER FAILURE)

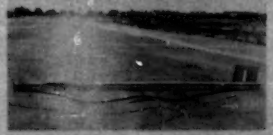
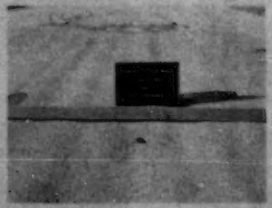
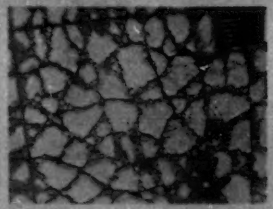


TEST CUT THROUGH 9.5" AC OVERLAY ON 10" PCC BASE PAVEMENT AFTER TRAFFIC (TRAFFIC WAS HALTED ON THIS ITEM IMMEDIATELY AFTER FAILURE)

FIGURE 3

TYPICAL AFTER TRAFFIC OVERLAY AND BASE PAVEMENT CONDITIONS

SHARONVILLE OVERLAY TEST TRACKS

	TRAFFIC CONTINUED AFTER FAILURE	TRAFFIC HALTED AT INCIPIENT FAILURE	TRAFFIC NOT SUFFICIENT TO PRODUCE FAILURE
OVERLAY	 SURFACE OF 12 INCH A.C. AND WATERBOUND MACADAM OVERLAY AFTER 135 COVERAGES	 SURFACE OF 24 INCH A.C. AND WATERBOUND MACADAM OVERLAY AFTER 3000 COVERAGES	SURFACE OF 24 INCH A.C. AND STABLIZED CRUSHED ROCK OVERLAY AFTER 3000 COVERAGES
BASE PAVEMENT	 SURFACE OF 6 INCH PCC BASE PAVEMENT AFTER REMOVAL OF 12 INCH OVERLAY (a)	SURFACE OF 6 INCH PCC BASE PAVEMENT AFTER REMOVAL OF 24 INCH OVERLAY (b)	SURFACE OF 6 INCH PCC BASE PAVEMENT AFTER REMOVAL OF 24 INCH OVERLAY (c)

NOTE: "COVERAGES" SHOWN ON INDEX SIGN IN PICTURES ARE ACTUALLY TRAFFIC PATTERNS. ONE TRAFFIC PATTERN IS EQUIVALENT TO SIX COVERAGES.

FIGURE 4

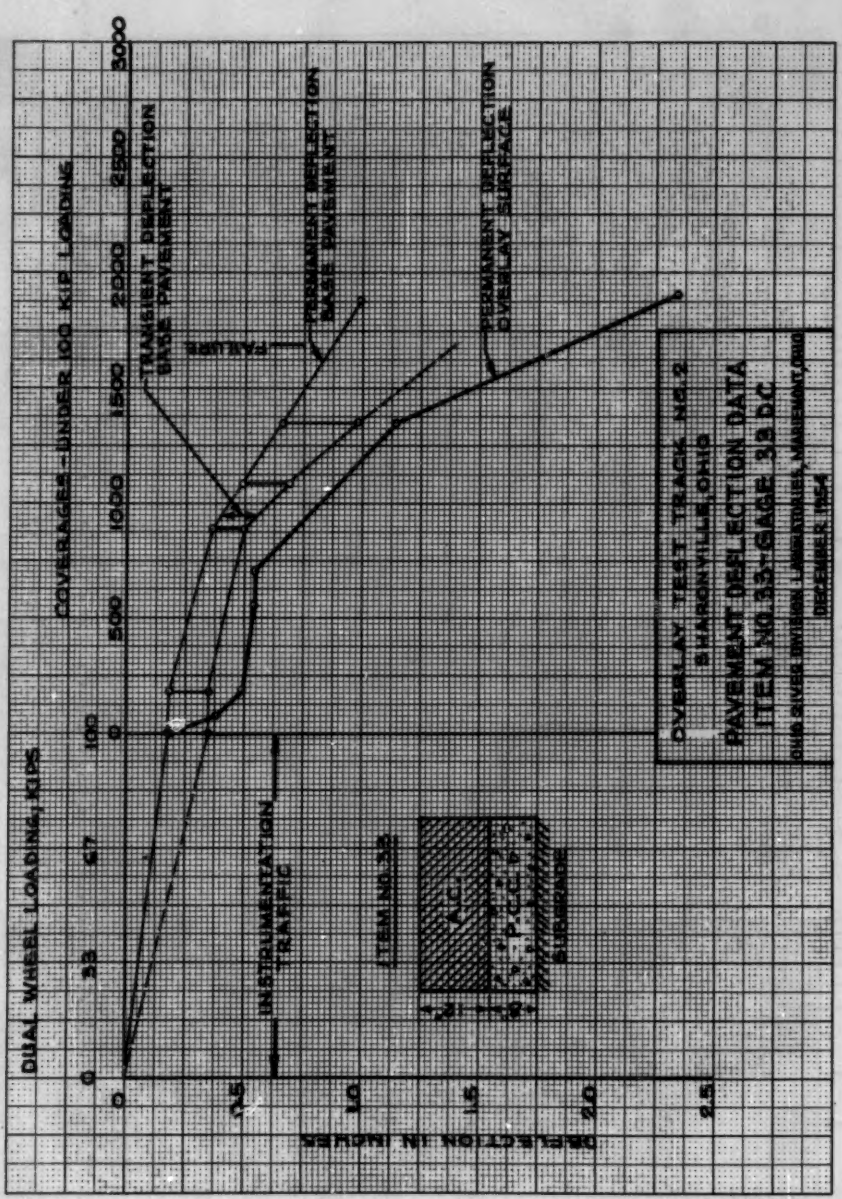

OVERLAY TEST TRACK NO. 2
SHANNONVILLE, OHIO
PAVEMENT DEFLECTION DATA
ITEM NO. 33 - GAGE 33 D.C.
OHIO RIVER DIVISION LABORATORIES, NAVIGATION BRANCH
DECEMBER 1954
PERMANENT DEFLECTION OVERLAY SURFACE
PERMANENT DEFLECTION BASE PAVEMENT
TRANSIENT DEFLECTION BASE PAVEMENT
FAILURE
COVERAGES - UNDER 100 KIP LOADING
DUAL WHEEL LOADING, KIPS
DEFLECTION IN INCHES
INSTRUMENTATION TRAFFIC
ITEM NO. 33
A.C.
P.C.C.
SUBGRADE

FIGURE 5

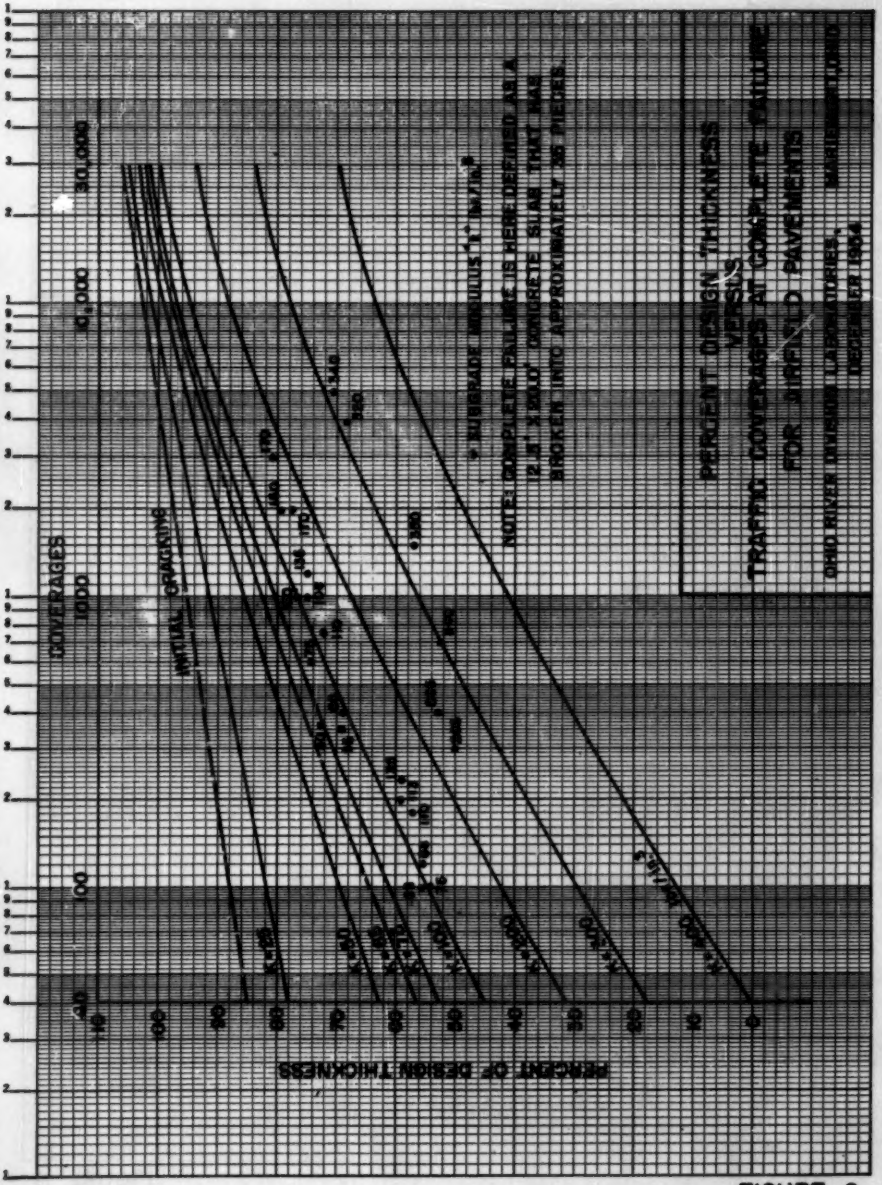

PERCENT OF DESIGN THICKNESS
COVERAGES
1000
10,000
30,000
INITIAL OPERATIONS
PERCENT DESIGN THICKNESS
VERSUS
TRAFFIC COVERAGES AT COMPLETE FAILURE
FOR
RIGID PAVEMENTS

FIGURE 6

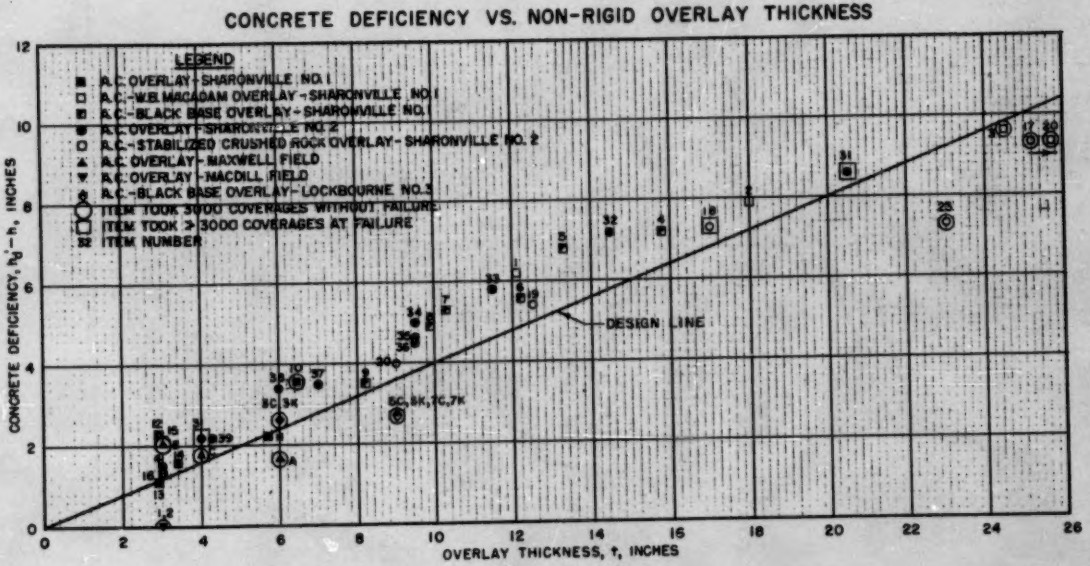
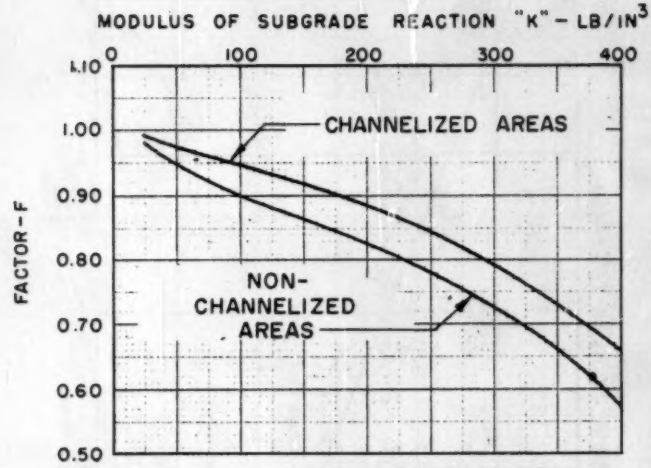

CONCRETE DEFICIENCY VS. NON-RIGID OVERLAY THICKNESS
LEGEND
A.C. OVERLAY - SHARONVILLE NO. 1
A.C. - W.B. MACADAM OVERLAY - SHARONVILLE NO. 1
A.C. - BLACK BASE OVERLAY - SHARONVILLE NO. 1
A.C. OVERLAY - SHARONVILLE NO. 2
A.C. - STABILIZED CRUSHED ROCK OVERLAY - SHARONVILLE NO. 2
A.C. OVERLAY - MAXWELL FIELD
A.C. OVERLAY - MACDILL FIELD
A.C. - BLACK BASE OVERLAY - LOCKBOURNE NO. 5
ITEM TOOK 3000 COVERAGES WITHOUT FAILURE
ITEM TOOK > 3000 COVERAGES AT FAILURE
32 ITEM NUMBER
DESIGN LINE
CONCRETE DEFICIENCY, h'd - h, INCHES
OVERLAY THICKNESS, t, INCHES
0
2
4
6
8
10
12
14
16
18
20
22
24
26

FIGURE 7

CORPS OF ENGINEERS U.S. ARMY

NON-RIGID OVERLAY DESIGN PROCEDURE



(1) DETERMINE FACTOR, F, FROM ABOVE CURVE.

(2) DETERMINE RIGID PAVEMENT DESIGN THICKNESS, h_d, REQUIRED FOR THE PAVEMENT FEATURE IN QUESTION (RUNWAY, TAXIWAY, APRON, ETC). THE FLEXURAL STRENGTH OF EXISTING PAVEMENT AND MEASURED SUBGRADE MODULUS "K" ARE USED.

(3) DETERMINE NON-RIGID OVERLAY THICKNESS REQUIRED FROM THE FORMULA,

$$t = 2.5\ [Fh_d - h]$$

WHERE t = REQUIRED NON-RIGID OVERLAY THICKNESS

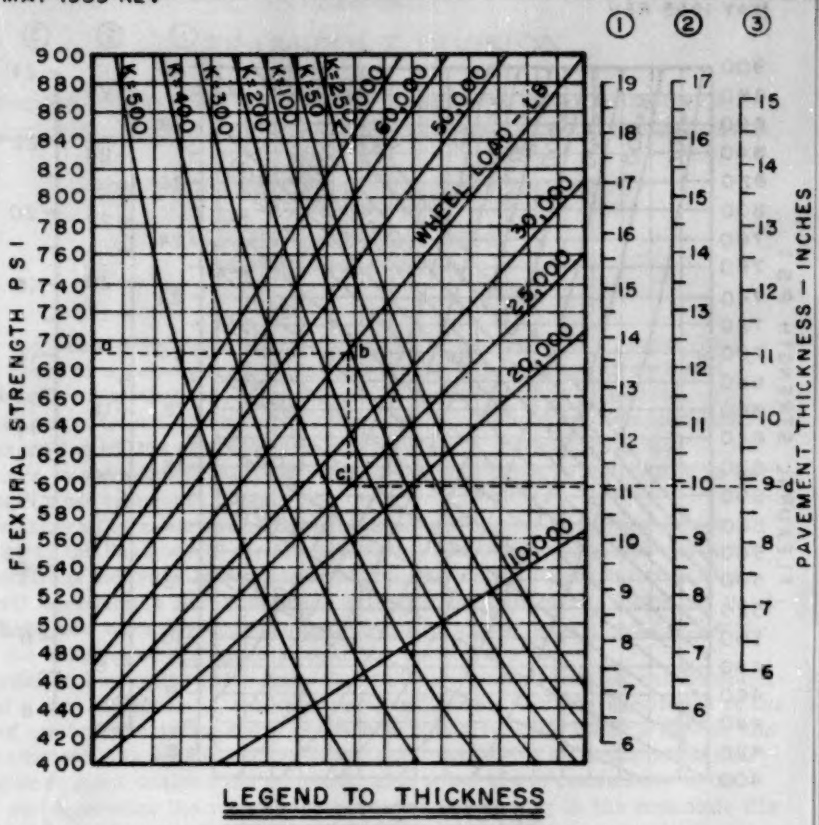
h = THICKNESS OF EXISTING RIGID PAVEMENT

(4) THE MINIMUM OVERLAY THICKNESS SHALL BE 4 IN.

FIGURE 8

CORPS OF ENGINEERS U.S. ARMY

MAY 1955 REV



LEGEND TO THICKNESS

① CHANNELIZED TRAFFIC AREAS: TAXIWAYS, APRON TAXIWAY.

② APRONS, 1000 FT. RUNWAY ENDS.

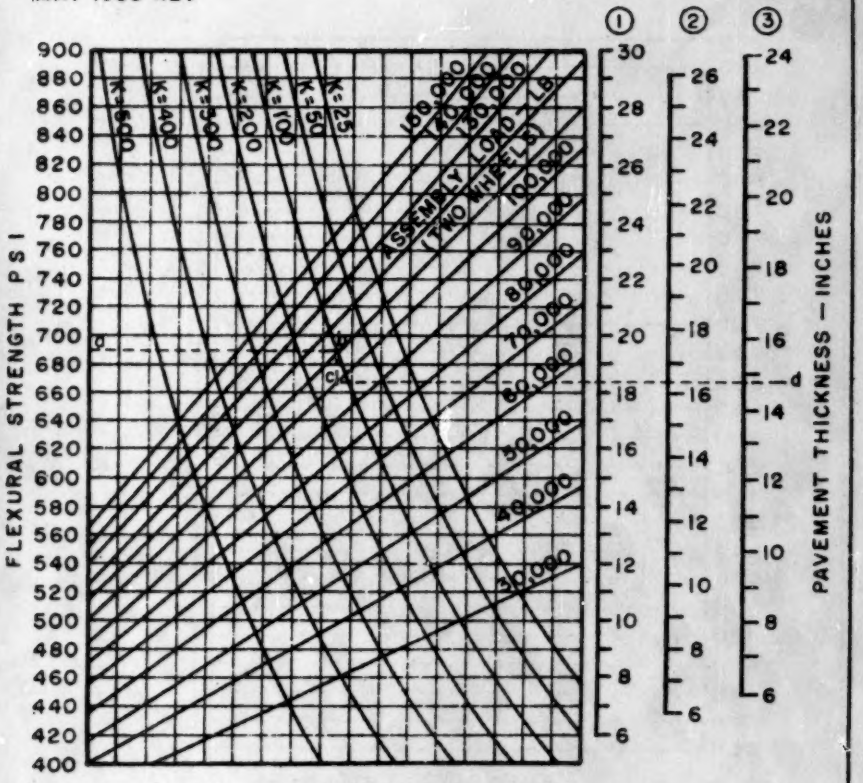
③ RUNWAY INTERIORS (AREA BETWEEN 1000 FT. RUNWAY ENDS.)

DESIGN CURVES FOR CONCRETE AIRFIELD PAVEMENTS SINGLE WHEEL 200 PSI

FIGURE 9

CORPS OF ENGINEERS U.S. ARMY

MAY 1955 REV



LEGEND TO THICKNESS

① CHANNELIZED TRAFFIC AREAS: TAXIWAYS, APRON TAXIWAY.

② APRONS, 1000 FT. RUNWAY ENDS.

③ RUNWAY INTERIORS (AREA BETWEEN 1000 FT. RUNWAY ENDS).

DESIGN CURVES FOR CONCRETE AIRFIELD PAVEMENTS TWIN WHEELS SPACED 37" C.C. CONTACT AREA 267 SQ. IN. EACH WHEEL

FIGURE 10

JOURNAL
AIR TRANSPORT DIVISION
Proceedings of the American Society of Civil Engineers

WHAT IS THE STORY OF AVIATION TODAY?

Joseph D. Blatt,[1] A.M. ASCE
(Proc. Paper 980)

The engineer in his approach to the design of a structural element—be it a simple beam or a complex indeterminate frame—first makes an estimate of the character, distribution and magnitude of the loads to be supported. The design of airports and air transportation facilities should not be approached as an exception to this general rule. Unfortunately, the civil engineer cannot as yet turn to a handbook, building code, or loading cable to assist him in estimating his air transport loads.

Even though the more common sources of load information may not be of much use to the designer of air transportation facilities, economic research and operations analyses have provided the engineer with the required clues. The Civil Aeronautics Administration believes that proper and sufficient yardsticks have now been developed to provide the engineer with a means of measuring the anticipated air operations at any proposed site.

In order to determine the magnitude of the air operations that can be anticipated at a specific location, the engineer must have a working knowledge of the status of air transportation today, know how it has reached today's levels, and from historical data establish trends and forecast future air transportation. The engineer must analyze the economic character of the community to be served and determine the role air transportation will play in the economic life of the community.

This paper will not attempt to answer the total loading problem, but will try to give some concept of aviation today—how big it is, its growth potentials, and its relationship to other forms of transportation.

Since the construction of airports and other air transportation facilities usually involve the expenditure of large sums of money, the engineer cannot design the facility to just meet today's aviation requirements, but must in some way guarantee the continued useful life of the structure through a long amortization. It is for this reason that in its day-to-day operations the CAA stresses the need for developing sound forecasts.

Note: Discussion open until October 1, 1956. Paper 980 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 82, No. AT 2, May, 1956.

1. Asst. Administrator for Planning, Research and Development, Civil Aeronautics Administration, U. S. Dept. of Commerce, Washington, D. C.

The problem must be approached with the well-entrenched premise that even though air transportation is relatively new, it is today a major medium of transportation in the United States. During the period since the close of World War II, U. S. Domestic and international air passenger traffic has more than doubled, while its air cargo has tripled in volume. During the same period, air commerce routes and services were extended agressively, transportation capacity modernized and expanded, and safety and dependability of operations greatly improved.

Fundamentally, air transportation is designed to serve people. It is therefore not surprising that the one best index of a community's total air commerce activity is the number of passengers served. Best index means that with a knowledge of the number of passengers served, the engineer can readily make an estimate of the tons of cargo to be handled, the number of aircraft that will be based at the location, the number of take-offs and landings that can be anticipated, the peak-hour operations, the number of gate positions required, etc.

The CAA utilized its passenger study to develop an air traffic hub classification system which is used by the agency for terminal area planning. The hub classification of a specific location, modified by population and economic character data, provides the CAA with a total estimating technique.

The growth of number of airline passengers carried in the domestic service by both the irregular and scheduled air carriers has been phenominal. In 1946, these carriers handled 12,200,000 passengers. By 1950, the figure had risen to 17,300,000. In 1954, 32,300,000 passengers were carried by the airlines. The CAA believes that a 1960 forecast of 55,000,000 passengers and a 1965 forecast of 70,000,000 passengers are realistic ones for the domestic airlines.

The 1960 forecast is a projection based on the rate of growth between 1950 and 1954 of 3.8 million passengers each year. The 1965 goal of 70,000,000 will mean an increase of 3,000,000 passengers each year for the 1961-1965 period. If helicopters, convertiplanes, or other steep-gradient aircraft are effectively developed so that they can exploit the true short-haul market, it is the author's belief that the forecast of 70,000,000 passengers in 1965 is much too low.

It might be interesting at this time to point out that in spite of the advent of non-stop transcontinental operations in the United States, the average length of passenger trips from 1946 to the present time has not varied very much. In 1946, the average length of passenger trips was 487 miles. Today, in spite of faster long-range aircraft, the average length of passenger trips is only 518 miles. The CAA believes that this trip length figure will not vary very much in the next decade.

Air cargo represents an increasingly important segment of U. S. commercial air traffic. Domestic air cargo includes the commercial air express and air freight carried within the continental United States by the scheduled airlines, the certificated all-cargo carriers, and the large irregular carriers.

The provision of adequate and efficient terminal facilities for an expanding air-cargo industry presents a challenge to the engineering profession. The rate of growth of air cargo will depend in part on the ingenuity of the engineer to improve present ground handling methods. Progress must be made in the field of palletizing air cargo and in the development of loading docks, storage facilities, and similar devices which should simplify loading and unloading of the aircraft and reduce ground handling time.

Air cargo has been essentially a post-World War II development, since air freight, the major segment of the air cargo service, was not available until near the end of the war. Despite air cargo's over-all record of growth, the industry's achievements today have been substantially below expectations.

Although the past two years have been disappointing for the industry, the long-range outlook now appears more promising than it has been for some time and a steady but modest pattern of growth seems assured. This optimism is premised on the prospect for the improvement of the aircargo industry's flight equipment. Up to the present time, the major part of the all-cargo fleet has consisted of surplus military C-46's and DC-4's also are in operation and a number of carriers have ordered additional one which are scheduled to enter service early in 1956. A further limited quantity of these aircraft is expected to become available under a proposed government lease program.

Carrier experience with the DC-6A indicates that its direct operating costs per ton mile are approximately 20 per cent lower than those attainable with the C-46 and DC-4. These costs may decline even further with fleet operations of DC-6A's. It is hoped that indirect costs may decrease as volume expands. This may bring about a reversal in the trend of cargo rates experienced in the past few years, and an actual reduction from present rate levels may be economically feasible, thereby improving the competitive position of air cargo.

In 1946, 32,593,000 ton miles of air cargo was handled in the domestic service. By 1950, the volume increased to 229,000,000 ton miles, and in 1954 the carriers handled 261,000,000 ton miles of air cargo. The volume of air cargo is expected to increase to approximately 500,000,000 ton miles by 1960, and 900,000,000 ton miles by 1965.

If these forecasts are realized, it is obvious that the engineering profession must be called upon to design efficient structures to accommodate this dynamic industry.

No status report on aviation would be complete without devoting considerable emphasis to the general aviation segment of the industry. General aviation is that broad base of aviation which includes all flying done by civil aircraft exclusive of air carrier operations. It includes pleasure and instructional flying, commercial flying, and business flying. By commercial flying is meant cargo and passenger transportation for hire (other than air carrier), commercial agricultural activities such as dusting, spraying, fertilizing, seeding and defoliation, and patrol, survey and other industrial activities.

Business flying is defined as the flight activities conducted by companies or individuals in carrying out in their own aircraft the operations of their given enterprises or professions.

In the past ten years, there has been a radical change in the character of general aviation. These has been a dramatic shift from instructional and pleasure flying to the current position in which business transportation, industrial applications, and transportation for hire occupy the dominant place. Business and commercial flying today accounts for 65 per cent of all general aviation flying hours.

It is obvious that flying today is no longer a rich man's sport but rather an integral part of the nation's economy. A listing of owners of corporate aircraft would read like a "Who's Who" of American business.

General aviation aircraft are expected to log 11.7 million hours in 1960, an increase of 2.9 million hours; that is a 33 per cent increase over 1954.

Every segment of general aviation is expected to increase during the next few years, but the most pronounced advance will occur in the business flying category. If general aviation continues to advance at the average annual increment of 488,000 hours forecase for the immediate future, it will reach the 14 million hour mark in 1965.

In the following paragraphs are outlined the status of U. S. international and overseas air commerce.

In 1954, the U. S. flag carriers operating in international and overseas air commerce handled nearly three times as many passengers as they did in 1946. Since 1946 the average trip length for passengers has been rather constant, varying from a high of 3,176 to a low of 1,254 miles. A relationship exists between the number of domestic and the number of international and overseas airline passengers. Between 1946 and 1954, international and overseas airline passengers varied from 8.5 per cent to 10.5 per cent of domestic airline passengers. Seven of the nine years have a variation within one per cent.

The CAA believes that a 1960 forecast of 5,000,000 passengers and a 1965 estimate of 6,000,000 international and overseas airline passengers are reasonable and conservative. 1960 and 1965 passenger mile forecasts of 6.5 billion and 7.8 billion passenger miles, respectively, have been based on an average trip length of 1,300 miles. Historical data indicate a rather stable trip distance pattern and no evidence exists to alter this fact as of today.

As the demand for dependability of operations increases and as the electronic art improves, the use of instruments in the landing of aircraft under adverse meteorological conditions also increases. This increase in low-visibility usage of airports will greatly influence the design of terminal facilities.

In 1948, only 209,500 instrument approaches were made within CAA air-route traffic-control-center areas. In 1951, the number of approaches increased to 383,300, and by 1954 approaches were being made at an annual rate of 515,700. By 1960 the CAA estimates that it will be handling approaches at a 900,000 annual rate, and by 1965 this rate will increase to 1,100,000 instrument approaches per annum.

The growth of aviation to date has in part been associated with the increases in population, annual income, and gross national product. It is interesting to note that historically the volume and amount spent for transportation services of all kinds has been closely correlated with our level of economic activity. Between 1946 and 1954, domestic inter-city travel expenditures approximated five to six per cent of the total gross national product.

The prospect of persistent economic growth points to further increases in total inter-city travel. The inter-city travel market consists of two major segments. The private automobile travel, the major segment of the inter-city travel market, represents 88 percent of the total. The common carrier segment of this market, including rail, bus and air, makes up the remaining 12 per cent.

Although total traffic has expanded sharply since 1946, almost all of this gain has been concentrated in the private automobile segment of the market. On the other hand, common carrier traffic has remained stable with decreases in rail and bus traffic offset by a marked advance in air traffic. In 1946, air travel amounted to only 6.5 per cent of the total common-carrier market. By 1950, this percentage increased to 14.2 per cent, and in 1954 we find that air

travel amounted to 28.5 per cent of the total common carrier travel.

Indications are that the pattern of the past few years will not change appreciably. It is estimated that the air transport share of the common-carrier market will rise from its current 29 percent to more than 50 percent by 1965. An expansion of this magnitude assumes that air transportation will not only increase its long-haul traffic but will also make substantial penetration of the medium- and short-haul travel markets.

It is the author's hope that, by presenting these rather startling statistics, he has been able to prove that aviation is big business today, has a prominent place in our national economy, and has great growth potentials. The author has attempted to demonstrate the dependence the aviation industry will have to place on the engineering profession and to express his hope that in the design of air transportation facilities the civil engineer will give adequate consideration to the present and future requirements of the aviation industry.

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A PATTERN OF INTERSTATION AIRLINE TRAVEL*

D. M. Belmont[1]
(Proc. Paper 987)

The forecasting of air traffic is an art greatly in need of reliable guiding principles. Long-range forecasting seems to be almost impossibly difficult. One can perhaps make what amounts to a lucky guess, but there is little basis for confidence in the result. Short-range forecasting is of course very much easier, and, in practice, much more important. Changes in airline service are usually based upon effects expected in the next few months or years, rather than in the next few decades. But short-range forecasting is by no means an exact science. Methods are sometimes used to support a forecast which will hardly bear critical examination. Successful forecasts may owe more to good intuition than to scientific basis.

It is the purpose of this paper to call attention to a typical pattern of interstation airline travel and to suggest a simple underlying law. The work is preliminary and tentative, and may raise more questions than it answers. It is offered in the hope that its development can provide a firmer ground for forecasting than is currently available.

When airline travel data are suitably organized, a rather remarkable pattern emerges, a pattern which suggests the following conclusion:

For stations more than about 800 miles apart, the number of trips between any two stations depends primarily upon the total traffic at each of them and upon the quality of service offered. It is independent of the distance between the stations.

To the extent that this law is valid, it should lead to easy calculation of the effect of important changes in quality of service. It will always be necessary to modify any such rule to accommodate local peculiarities, but the rule may at least provide a useful first approximation.

The pattern is exhibited in Figs. 1 to 10. Fig. 8 shows traffic[2] involving

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2. The data throughout the paper are from the domestic section of Civil Aeronautics Board. Origin-Destination Airline Revenue Passenger Survey, September 17-30, 1954.

Dallas. Each point represents one of the other 61 large or medium hubs, showing the travel between the hub and Dallas in proportion to the former's total traffic. For example, the uppermost square is for travel between Dallas and New Orleans (440 miles apart). This amounted to 1,140 passengers in the survey period, while the total traffic at New Orleans was 21,102 passengers. The ratio of 1,140 to 21,102 is 0.054, the value plotted.

It will be observed that the points decrease in height as distance increases to about 800 miles but that thereafter they lie in a substantially horizontal band. In particular, the squares, representing station-pairs having non-stop service, show this pattern rather clearly.

Figs. 3 to 10 are striking similar. In each, for long-distance travel, the squares lie roughly on a horizontal line. The solid circles (station-pairs having one-stop, through-plane service) lie also nearly horizontally, a little below the level of the squares, on the average. Lower still is a horizontal band of open circles, representing cities having less direct airline connection. Certain deviations from the pattern occur:

1. Traffic with Miami, Tampa, Minneapolis, and Fort Worth is often distinctly too high.
2. The critical distance of 800 miles holds pretty well for most cities. For Denver, Los Angeles, San Francisco, and Seattle, however, a greater distance applies, perhaps 1,200 miles.

There is a venerable theory of transportation which holds that the traffic between two centers is proportional to the product of their populations, and inversely proportional to the distance between them:

$$T_{AB} + k \frac{P_A P_B}{D_{AB}}$$

where T_{AB} is the number of trips between centers A and B, in a given period,

P_A and P_B are the respective populations of A and B,

D_{AB} is the distance between them,

and k is a constant, independent of A and B.

This law may have some applicability to short-distance airline travel. For long-distance travel, however, the horizontal tendency shown in the charts strongly suggests that the distance between stations has little or no effect on the airline travel between them.

Suppose instead that long-distance travel A and B is proportional simply to the product of their effective populations:

$$T_{AB} = k P_A P_B$$

The population served by an airport is not easily determined, and the effective population (in the sense required by the formula) is not necessarily equivalent to a counting of heads. For our purpose it is expedient to substitute the station's total airline traffic, T_A or T_B, for P_A or P_B. The total traffic of a station is a definite number and one which should reflect population closely enough.

We assume then that, for A and B at long distance,

$$T_{AB} = k\, T_A T_B$$

$$\text{or that the ratio } \frac{T_{AB}}{T_A T_B} = \text{constant}$$

Fig. 1 shows this ratio[3] "normalized interstation trips," for station-pairs having non-stop service. The points shown represent trips between the 21 largest hubs and all suitably served large or medium hubs[4] with interstation distance over about 800 miles, or over 1,200 miles for points involving Denver, Los Angeles, San Francisco, or Seattle. Fig. 1 thus brings together the (long-distance) solid squares of charts such as Figs. 3 to 10, with their values put on a comparable footing by dividing them by the base station's total traffic. Table 1 identifies the stations involved, and provides a sample calculation.

Fig. 2 and Table 2 also shown normalized interstation trips, but for station-pairs with one-stop, through-plane service as the most direct connection.

It will be seen that the points of Fig. 1 are in fair agreement with our assumption. They lie rather uniformly in a horizontal band, supporting the theory that the distance between stations is irrelevant to traffic between them. There is of course considerable scatter amongst the points—they do not lie on a line. This is to be expected because of wide differences in quality of service, special community of interest, etc. (Perhaps some of the scatter is due to the use of our normalizing function; a better one might pull the points together more.)

In Fig. 2, for one-stop routes, the points appear to decrease as distance increases. This variation from the horizontal, however, is not very pronounced. To call the points independent of distance is about as accurate as to call them inversely proportional to distance.[5]

A noteworthy difference between Figs. 1 and 2 is in the average height of their points. Excluding the abnormally high points (open circles) the average for Fig. 1 is 32.7; for Fig. 2 it is 23.5. This suggests that changing from one stop to non-stop service will, on the average, increase the interstation traffic by about 40%. Such a rule, if valid, would offer a very useful starting-point for forecasting the effect of improvement in airline service. It would be especially useful if it could be refined to apply to several degrees of quality of service.

The true significance of the patterns exhibited in this paper depends upon the answer to a host of questions not yet investigated. Are the patterns the same for small hubs? Can the method be extended to shorter distances? Does the pattern change from year to year? Is September traffic typical (in

3. Multiplied by 10^6, for convenience.
4. Excluding Miami and Tampa.
5. The standard deviation (excluding the points shown as open circles) is 8.2 for the assumption of independence of distance, and 6.8 for the inverse distance law.

the required respects) of the year-round traffic? How much of the scatter in Fig. 1 is due to differences in quality of service? Are differences between Figs. 1 and 2 due to differences in size among the cities represented? Why does distance have so little effect on airline travel?

Only the last question is perhaps easy to answer. The farther apart the stations are, the greater the advantage of air travel over competing forms. If total interstation travel, by all modes, was inversely proportional to distance, the airline portion would be greater for longer interstation distance, and would tend not to decline with distance. A more important reason may be that the airlines have succeeded to a considerable degree in eliminating distance as a factor in travel. The difference in time between alternate destinations is relatively small, and one can cross the country for little more than it costs to go from San Francisco to Dallas. Whatever the future of air transport, it seems safe to predict that operations at the airline terminal will be of increasing importance both in airline costs and in passengers' total travel time. Interstation distance will matter very little.

TABLE 1-- NORMALIZED INTERSTATION TRIPS AND INTERSTATION DISTANCES-- NON-STOP ROUTES-- Sept. 17-30, 1954

		Normalized Trips**	Distance
New York	-- Atlanta	41	760
	Dallas	27	1380
	Denver	29	1630
	Houston	35	1430
	Jacksonville	46	840
	Los Angeles	38	2475
	Memphis	27	970
	Minneapolis	41	1020
	New Orleans	43	1190
	San Francisco	34	2580
	St. Louis	41	890
	Tulsa	25	1230
Chicago	-- Boston	34	860
	Dallas	38	800
	Fort Worth	23	815
	Los Angeles	40	1750
	New Orleans	27	830
	Phoenix	30	1450
	San Francisco	33	1860
	Seattle	24	1900
Los Angeles	-- Dallas	28	1245
	Fort Worth	53*	1220
	Kansas City	34	1370
	St. Louis	32	1600
	Washington	26	2330
San Francisco	-- Dallas	19	1530
	Fort Worth	30	1500
	Kansas City	24	1510
	Tulsa	25	1470
Washington	-- Dallas	25	1180
	Denver	36	1510
	Fort Worth	58*	1220
	Houston	28	1220
	Memphis	36	760
	New Orleans	44	970
Dallas	-- Cincinnati	33	860
	San Diego	33	1180
Seattle	-- Minneapolis	55*	1400
Minneapolis	-- Salt Lake City	67*	1120
	Spokane	56*	1175
Kansas City	-- Phoenix	40	1050

---

*Omitted in following statistics:

Normalized Trips -- mean 32.74

variance 44.13

**Example of calculation:

Total trips to or from New York = 273,023

Total trips to or from Atlanta = 33,689

Trips between New York and Atlanta = 3,742

Normalized trips between New York and Atlanta = $\frac{(3,742)10^8}{(273,023)(33,689)} = 41$

TABLE 2-- NORMALIZED INTERSTATION TRIPS AND INTERSTATION DISTANCES--
ONE-STOP ROUTES-- Sept. 17-30, 1954

		Normalized Trips	Distance
New York	— Birmingham	38	870
	Fort Worth	28	1410
	Kansas City	29	1100
	Phoenix	20	2170
	Salt Lake City	16	1980
	Seattle	19	2620
	Spokane	14	2200
Chicago	— Albuquerque	25	1130
	Houston	33	1040
	Jacksonville	29	860
	Portland	18	1830
	Salt Lake City	25	1260
	San Antonio	42	1045
	San Diego	30	1860
Los Angeles	— Birmingham	9	1850
	Buffalo	17	2220
	Cincinnati	14	2000
	Detroit	26	1970
	Minneapolis	40*	1770
	New Orleans	17	1680
	Omaha	32	1330
	Philadelphia	23	2450
	Pittsburgh	18	2155
	San Antonio	23	1495
San Francisco	— Cleveland	13	2160
	Hartford	21	2630
	Memphis	8	1950
	New Orleans	16	1970
	Pittsburgh	11	2280
	Washington	29	2515
Washington	— Kansas City	30	950
	Omaha	37	1020
	Tulsa	27	1050
Detroit	— Denver	21	1130
	Spokane	16	1690
Boston	— Atlanta	18	950
Cleveland	— Denver	22	1220
	Fort Worth	30	1065
Pittsburgh	— Jacksonville	39	830
	Phoenix	9	1835
Philadelphia	— Dallas	18	1300
	Denver	26	1580
	Kansas City	53*	1040
	Fort Worth	52*	1330
	Memphis	31	880
St. Louis	— Albuquerque	30	950
Dallas	— Phoenix	27	880
Minneapolis	— Portland	31	1450
Denver	— Hartford	24	1685

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*Omitted in following statistics:

Normalized Trips -- mean 23.46
variance 67.42

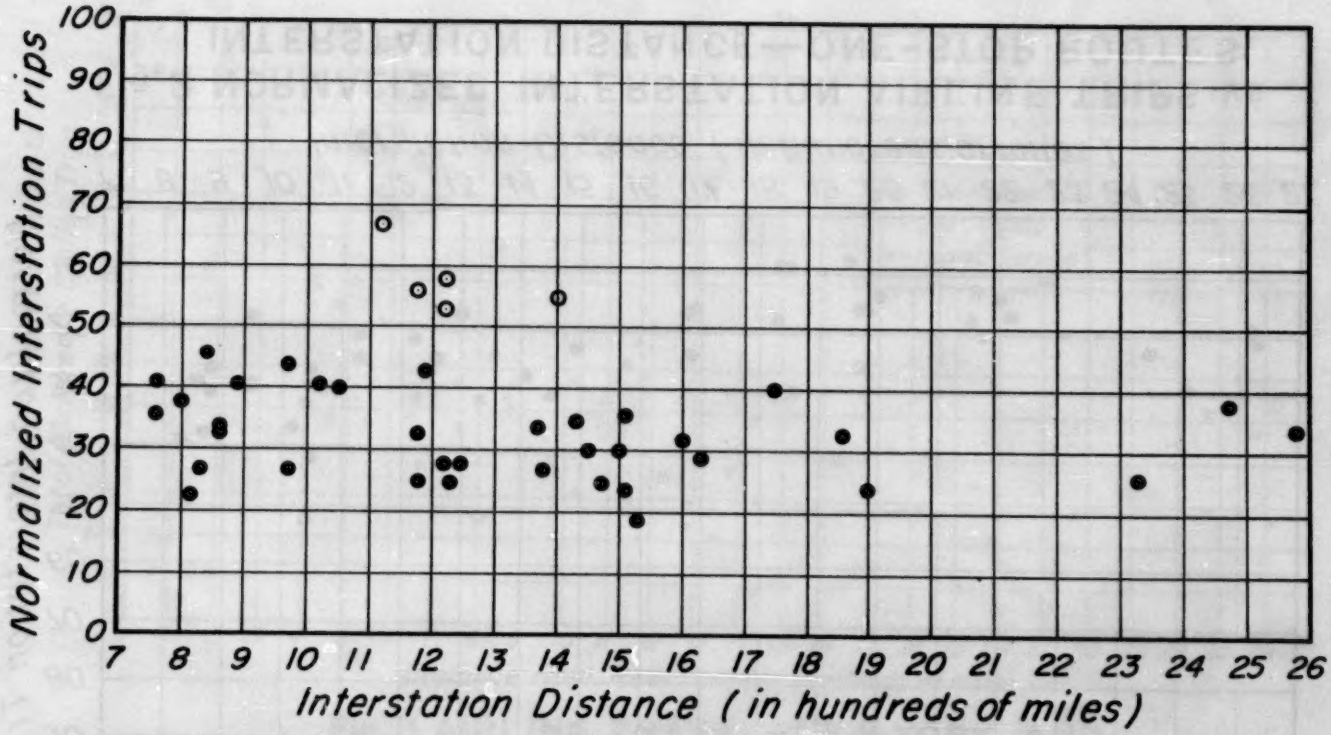

Fig. 1 NORMALIZED INTERSTATION AIRLINE TRIPS vs INTERSTATION DISTANCE—NON-STOP ROUTES.

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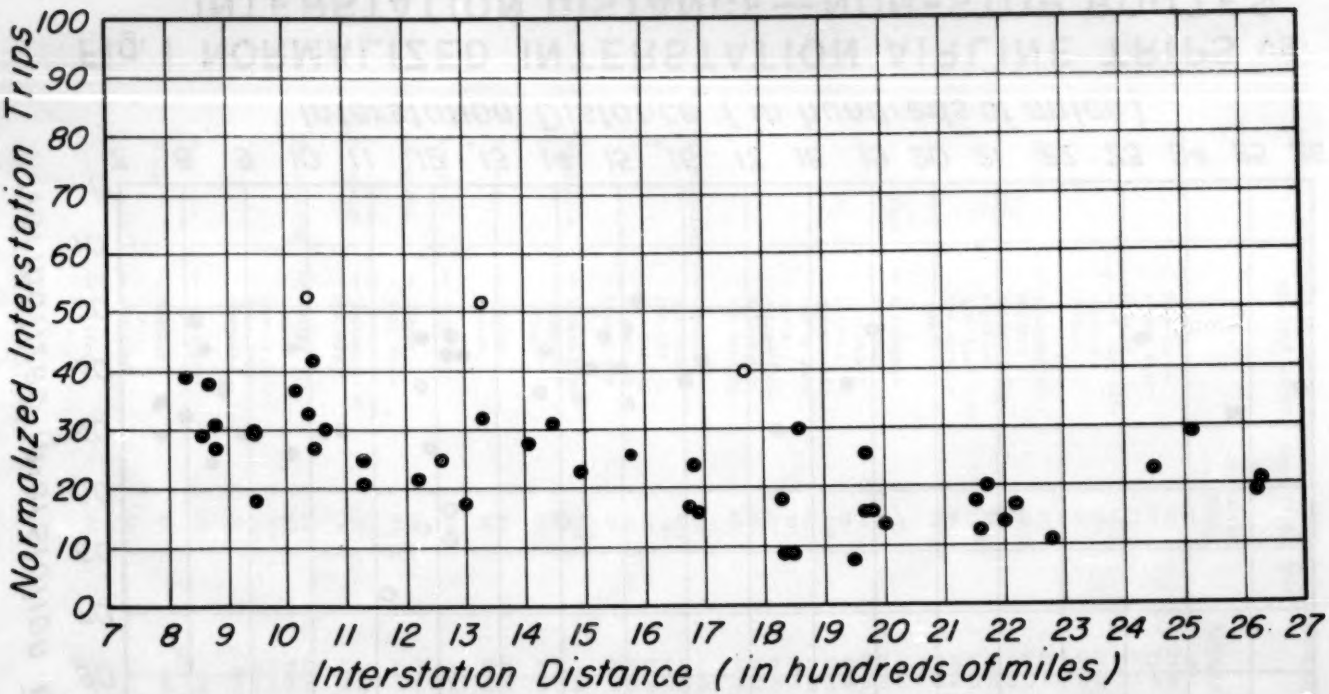

Fig. 2 NORMALIZED INTERSTATION AIRLINE TRIPS vs INTERSTATION DISTANCE—ONE-STOP ROUTES.

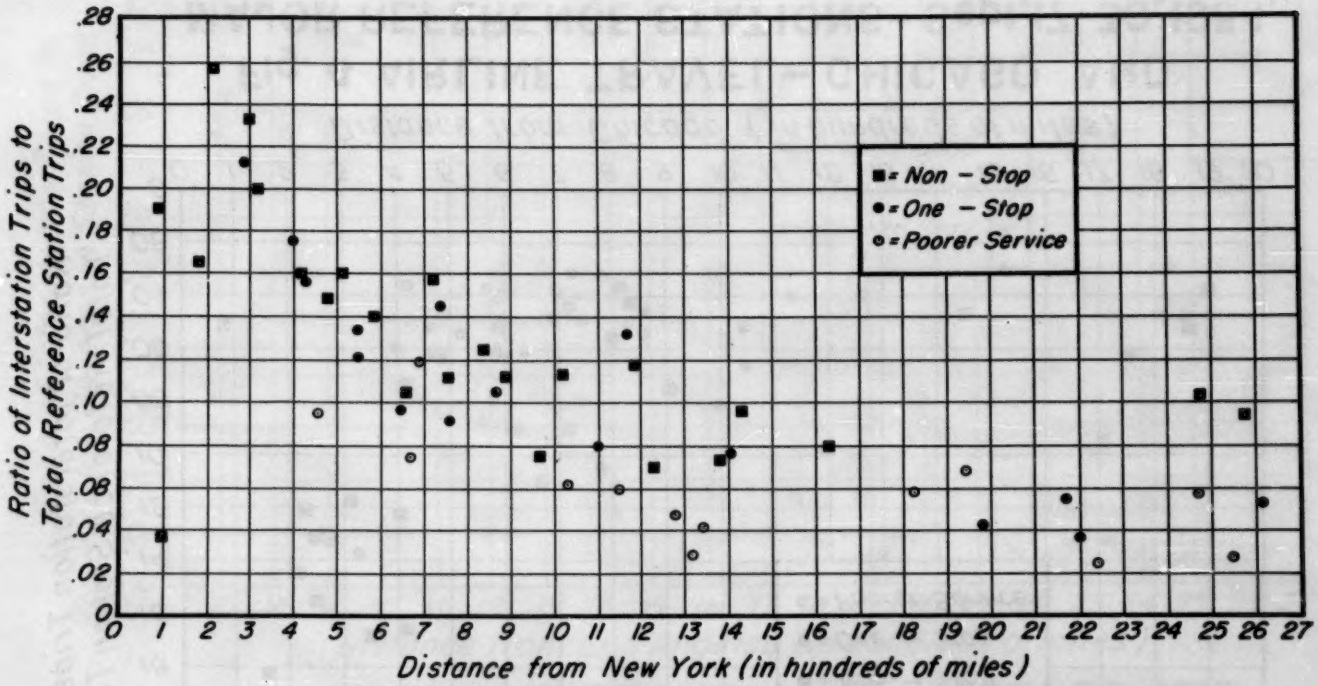

Fig. 3 AIRLINE TRAVEL- NEW YORK AND MAJOR REFERENCE STATIONS-Sept. 17-30, 1954.

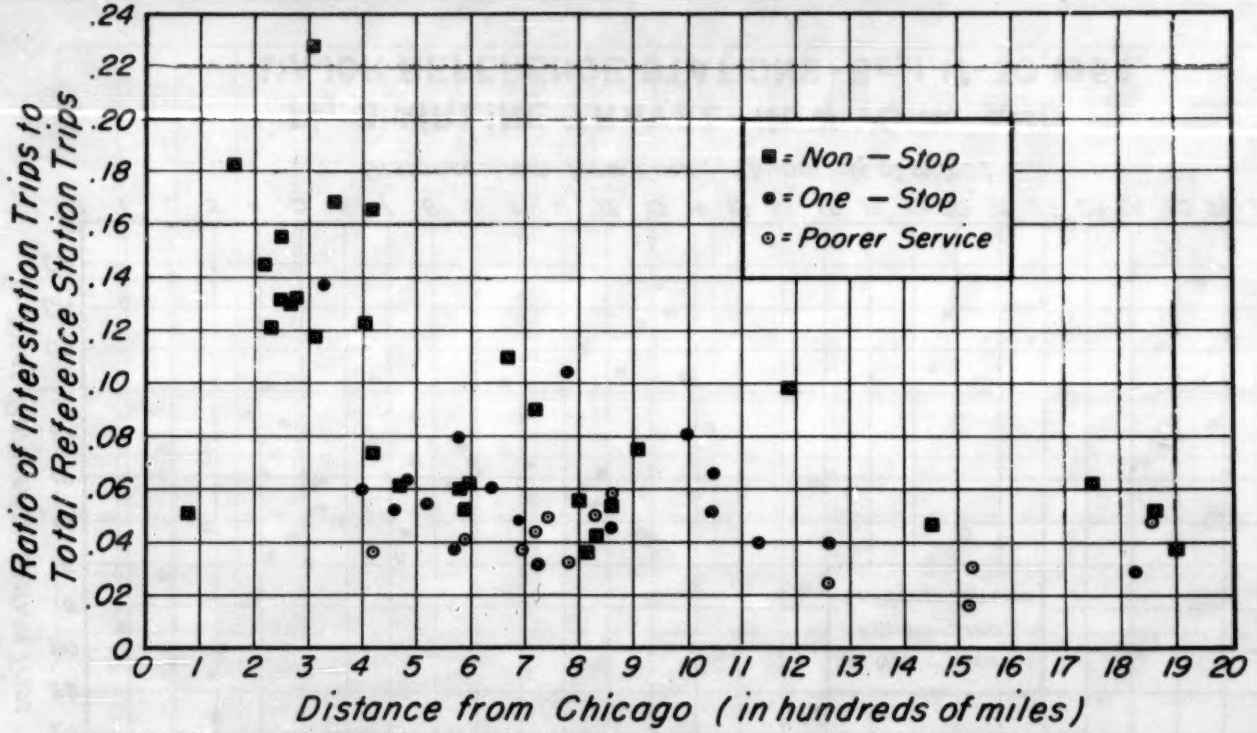

Fig. 4 AIRLINE TRAVEL– CHICAGO AND MAJOR REFERENCE STATIONS– Sept, 17–30, 1954.

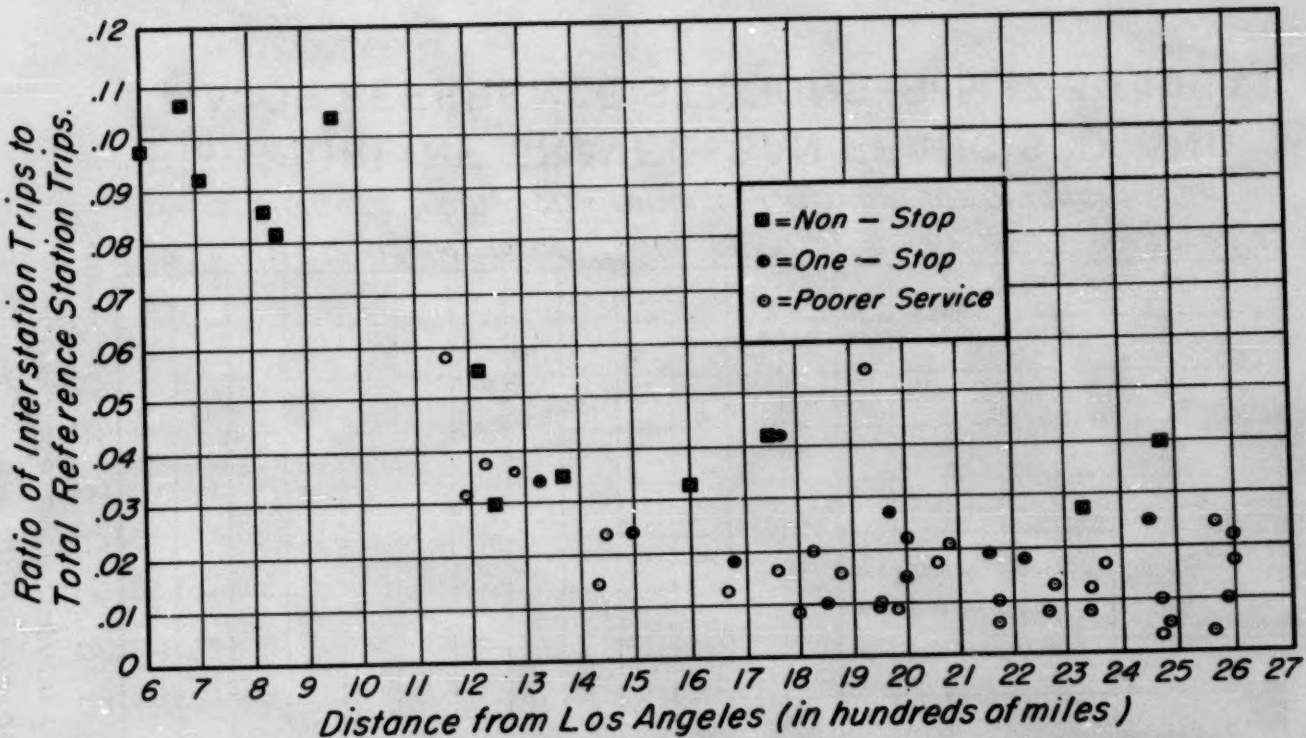

Fig. 5 AIRLINE TRAVEL–LOS ANGELES AND MAJOR REFERENCE STATIONS–Sept. 17–30, 1954.

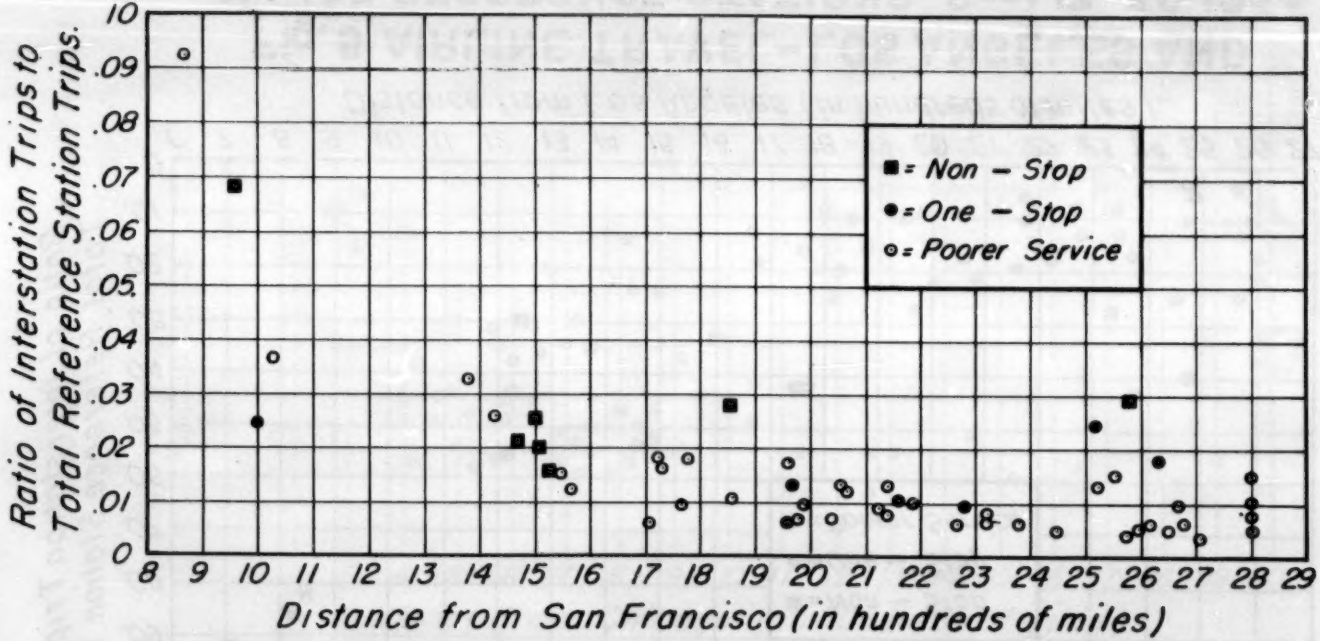

Fig. 6 AIRLINE TRAVEL–SAN FRANCISCO AND MAJOR REFERENCE STATIONS–Sept, 17-30, 1954.

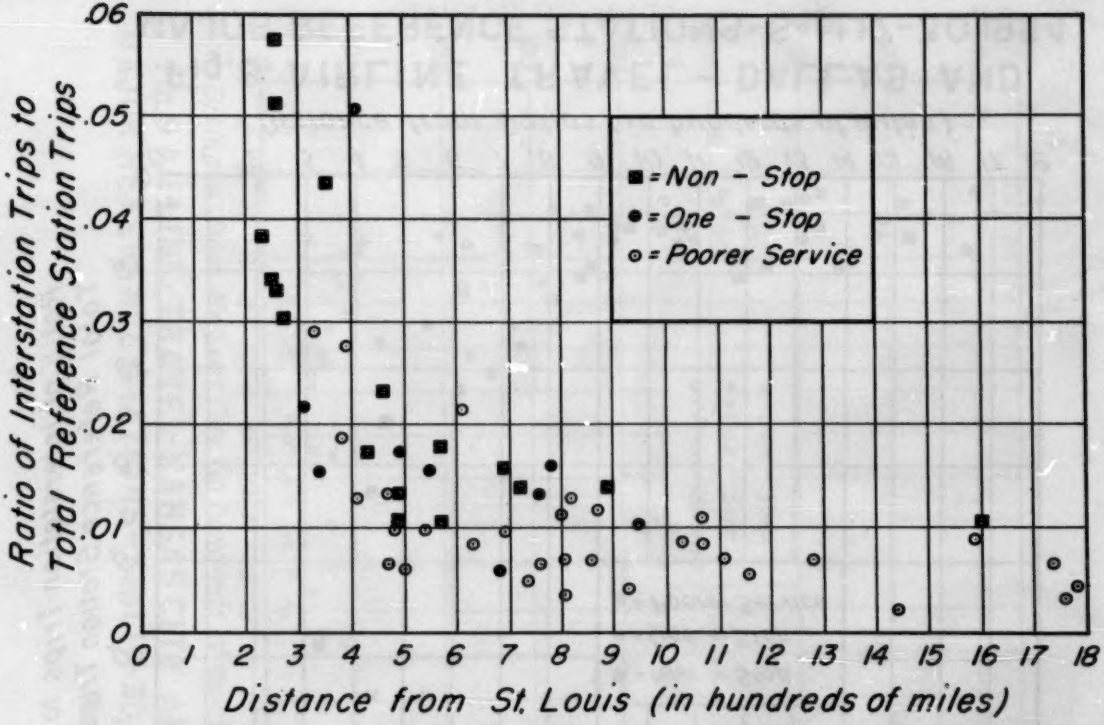
Ratio of Interstation Trips to Total Reference Station Trips
.06
.05
.04
.03
.02
.01
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Distance from St. Louis (in hundreds of miles)
■ = Non - Stop
● = One - Stop
⊙ = Poorer Service

Fig. 7 AIRLINE TRAVEL- ST. LOUIS AND MAJOR REFERENCE STATIONS Sept. 17-30, 1954.

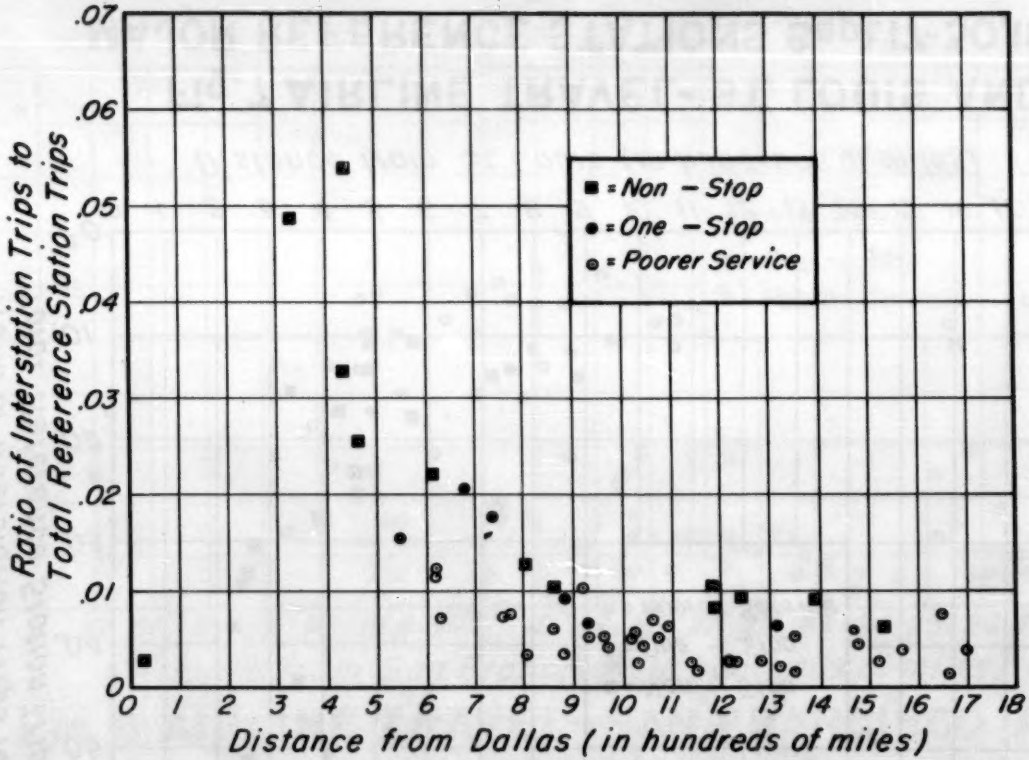
Ratio of Interstation Trips to Total Reference Station Trips
.07
.06
.05
.04
.03
.02
.01
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Distance from Dallas (in hundreds of miles)
■ = Non – Stop
● = One – Stop
◎ = Poorer Service

Fig.8 AIRLINE TRAVEL– DALLAS AND MAJOR REFERENCE STATIONS-Sept.17-30,1954.

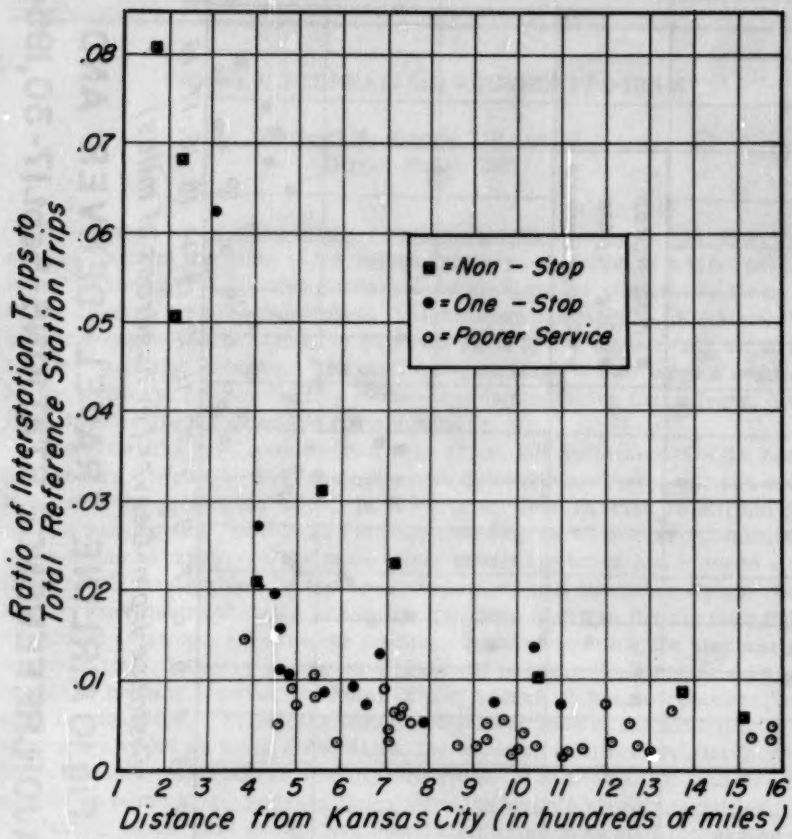

Fig. 9 AIRLINE TRAVEL-KANSAS CITY AND MAJOR REFERENCE STATIONS - Sept. 17-30, 1954.

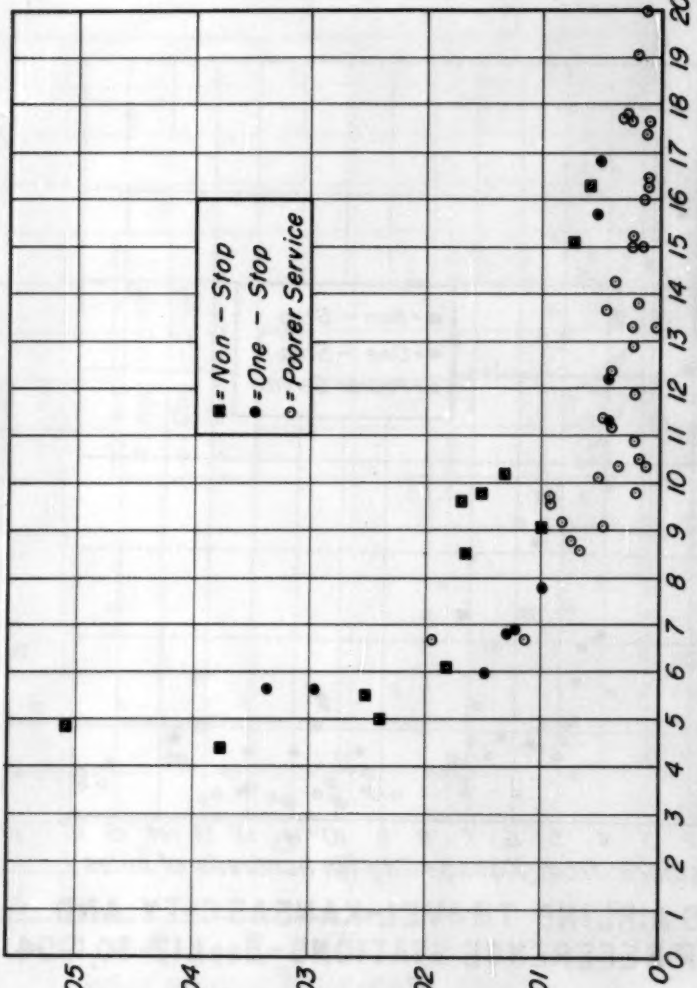
Ratio of Interstation Trips to Total Reference Station Trips
.05
.04
.03
.02
.01
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20+
Distance from Denver (in hundreds of miles)
■ = Non - Stop
● = One - Stop
○ = Poorer Service

Fig. 10 AIRLINE TRAVEL - DENVER AND MAJOR REFERENCE STATIONS - Sept. 17-30, 1954.

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THE NEW FEDERAL-AID AIRPORT PROGRAM*

Herbert H. Howell,[1] M. ASCE
(Proc. Paper 989)

A better understanding of any aviation discussion may be had, if at the outset one looks at the state of the entire industry. Aviation is a vital part of today's economy. Civil and military aviation together combine to make one of the country's major industries. The military segment is, of course, the larger segment and it is due, in no small part, to our ever-ready air arm that we can exist in peace. The civil side, although not as large a segment as the military, gives a healthy picture and is something that affects, directly or indirectly, the daily life of each citizen.

The growth of civil aviation has been rapid, but sustained. On the basis of passengers carried by U.S. domestic scheduled air carriers, one can realize how great the growth has been. In 1948 the airlines carried 13 million domestic passengers. In 1955, 35 million passengers were carried—almost three times as many. At the same time, general aviation has enjoyed a similar growth, particularly in the area of business and executive flying. Actually, last year business flying accounted for more hours in the air than did scheduled aviation. All over the country, industry is using the airplane as a business tool. Industry is decentralizing and is using the airplane as a means of knitting together the home office, branch plants, warehouses, and area headquarters. Expanding industries tend to look to the existence of an adequate airport as being a requisite, the same as utilities, availability of labor and raw materials in seeking new sites. It is known that industry has passed up some towns because there were inadequate airport facilities.

Healthy as the past growth has been, civil aviation is still increasing and will continue to do so. Civil Aeronautics Administration forecasts indicate that the 35 million passengers carried in 1955 will double in the next ten years, reaching 70 million passengers in 1956. Similar growth is estimated for other phases of civil aviation.

Note: Discussion open until October 1, 1956. Paper 989 is part of the copyrighted Journal of the Air Transport Division of the American Society of Civil Engineers, Vol. 82, No. AT 2, May, 1956.

* Dallas, Texas, Convention, American Society of Civil Engineers, February 14, 1956.

1. Director, Office of Airports, Civil Aeronautics Administration, Washington, D.C.

As the aviation industry grows, more and more demands are placed on airports. These demands can be translated into longer, stronger runways, adequate taxiways, ample parking areas, and terminal buildings that can handle large numbers of passengers.

The jet age will put further demands on airports. The air carriers have ordered large numbers of turbine-powered craft and they will be placed in service in 1959 or 1960. It appears that jet aircraft will put many unique demands on our airport system. The CAA, together with industry, has already set the wheels in motion to identify these problems and seek logical solutions. Already, many fears of airport operators have been allayed, but problems will arise, although none that are insurmountable.

The jet transport aircraft, as currently proposed, have wing spans of about 140 feet, lengths about 145 feet, and gross weights up to 280,000 pounds. Airport lengths are, generally, compatible with our present Technical Standard Order N6a. The orders, however, will be reviewed thoroughly as we learn more about jet requirements. Pavement strengths are not unreasonable, as the aircraft will be equipped with dual-tandem landing gear; in other words, four wheels in each of the two main landing gear struts. This weight distribution spreads the load so it can be carried by pavements of reasonable thickness.

There are numerous other problems facing us with regard to jets, not the least of which is noise. We do have some assurance that current studies offer promise of quieter jet aircraft. Also, there is the problem of terminal areas. The jets will accommodate well over a hundred passengers—up to perhaps 150 in coach versions. What terminal that we now have can handle, at one ticket counter, 150 passengers boarding a single flight?

To get deeper into the airport picture, it should be borne in mind that this is perhaps the only country in the world that leaves to the local community the initiative for providing adequate airport facilities. The only Federally-operated civil air terminal in the country is at Washington—the Federal capital. Federal assistance has normally been available in one form or another, but the actual initiative and prime responsibility is vested in the local government—state, county, or city.

Such Federal assistance that has been available can be grouped under three general heads. First, the work-relief programs of the 1930-1940 era, when aviation was in its first period of sustained growth.

Second, during World War II when funds were made available for airports for military use or to serve defense needs. At the end of the war these airports came into civil use through reversion or as surplus property. Third was the Federal-aid Airport Program.

The Federal-aid Airport Program was authorized by Congress in 1946. It was started in 1947 and has been under way since that time. In the first seven years of the Program, appropriations varied from a high of $42 million to a low of $10 million. In 1953, there was no appropriation. Rather, the year was spent in studying the program and examining the proper role of the Federal government in airport development. At the conclusion of the study, it was determined that the Federal government had a necessary and proper role to play in assisting local governments in the provision of an adequate national system of airports.

Our airports form a system that is truly national in scope. This can be demonstrated by figures available from origin and destination surveys conducted by the Civil Aeronautics Board. New York, for instance, in 1955, was the point of arrival or departure for over 8,000,000 passengers. They went in large volumes to some cities—nearly 800,000 to and from Chicago, over 700,000 to and from Boston, over 600,000 to and from Washington, nearly half a million to Miami, over 300,000 to Los Angeles. The number of passengers was more than 100,000 to ten other cities, and more than 50,000 to nineteen additional cities. Los Angeles, the largest hub on the west coast, was the focal point for nearly 3,500,000 domestic passengers in 1955. The pattern is the same as New York, but with fewer passengers—more than 100,000 passengers to and from six cities; more than 50,000 to seven other cities, and more than 25,000 to ten additional cities. But both New York and Los Angeles exchanged passengers with nearly all of the 550 communities served by the airlines. Using as an example Riverton, Wyoming, we find that it had a significant exchange of passengers with both Los Angeles and New York—more than 200 to each. Here is the national significance—the people of Riverton have a vital interest in the existence of adequate airport facilities in New York and Los Angeles. Likewise, people in New York and Los Angeles have a vital interest in adequate facilities in Riverton, Wyoming—if there is to be air commerce between them and Riverton.

Consider the Dallas-Fort Worth area. Nearly 2,000,000 people were carried to and from this important metropolitan area last year. More than 100,000 passengers were exchanged with New York, Chicago, Houston, and San Antonio. More than 50,000 passengers were exchanged with Los Angeles, New Orleans, Oklahoma City, Tulsa, Austin, and Midland; more than 25,000 with eleven other cities; more than 10,000 passengers with sixteen additional cities. Altogether there was traffic to and from some 350 cities—and 145 passengers were exchanged with Riverton, Wyoming! The average airliner left the area with fifteen local passengers on board, each of whom flew an average distance of 634 miles.

In a like manner, we can look at the airports used by business and executive flying. J. I. Case, a farm equipment manufacturer, has a fleet of three airplanes. In 1954 those three planes, a small fleet compared to some companies, used some 400 airports in the conduct of Case business. The coverage was nationwide, affecting all but three states. Airports have to be considered on a system basis—one alone has little value. Someone has asked—how would you like to have the only telephone in the country?

Referring again to the Federal-aid Airport Program the year's study proved that there was a legitimate role for the Federal government to play in airport development. As a result, Congress appropriated $20 million in 1954 and a like amount in 1955.

During this first phase of the program a total of $234 million was appropriated for airport development. This has gone into some 2,700 projects at about 1,200 airports.

The second phase, or the "new" Federal-aid Airport Program came about with the approval by the President of Public Law 211 last August. This new Law amends the Federal Airport Act of 1946 to provide for a four-year program. The Act authorizes obligations in the amount of $42.5 million in 1956,

and in the amount of $63 million in each of the fiscal years 1957, 1958, and 1959. In its simplest form, the Federal-aid Airport Program is now similar to the Federal-aid Highway Program.

As a result of the new law, the Department of Commerce and the CAA, with the assistance of an industry advisory panel, undertook a complete review of its policies, procedures and standards. This review was completed in near-record time and announced just ten weeks after approval of the new law. A booklet was issued early in October 1955 announcing these new policies and procedures. In the general area of policy, there is no major change from those in operation during the first phase of the program. The Planning Standards now gear eligibility to a forecast of aeronautical necessity. The Planning Standards recognizes two major developments; first, that the Feeder-category airport is no longer valid, on a long-range basis, for local-service airlines; and second, that in the general aviation area, executive flying needs more airports of the Feeder category.

The Programming Standards govern the eligibility of individual items of work. Generally, all types of airport development are eligible except hangars, if for public use. In programming the allocation of Federal funds, highest priority is given to items of safety, than to items which contribute to efficient operation, and finally, work that is essentially for convenience.

The first results of the new policies can be judged on the basis of the 1956 program allocating some $40 million to about 300 airports of all types.

In actual operation, available funds, or authorizations, are apportioned among the states on an area-population formula, with 25% being retained as a discretionary fund to be used in those states with more projects than can be financed from the state apportionments. Sponsors, local governmental units, file project requests which are considered in developing annual programs.

Annual programs are developed from an analysis of each increment of work proposed in each project request, and within the limits of available Federal funds. Tentative allocations of funds are made to individual projects; these funds remain allocated as long as the sponsor is diligent in developing plans, specifications, and project documentation. When a formal application, together with plans and specifications, is submitted to and approved by the CAA, a grant offer is made. When this is executed by the local sponsor, it becomes a grant agreement and is a contract with the government. The local agency is responsible for the preparation of plans and specifications. It awards the contract and supervises the construction work. The sponsor submits periodic estimates on which Federal payments are based. The normal Federal share is 50% of the total cost, except in the so-called "public land" states.

In some states, particularly in the west, the area-population formula apportions more funds than can be matched by local sponsors. The law provides that, after having been available for two years, unused state apportioned funds are redistributed, again on the same area-population formula. This prevents the building up of large amounts of unused funds.

The program operates, it is believed, with a minimum of red tape and with the maximum possible authority delegated at the "grass roots" level. The CAA has a relatively small organization which functions through four Regional Offices and twenty District Offices.

The new program gives assurance of four years of Federal assistance to airport development. Of most importance, however, is the fact that it permits sponsors to do a better job of long-range planning and not gear airport development to a one-year appropriation with an uncertain future.

Aviation will continue to grow—that means greater demands on our airports. This demand can best be met through intelligent long-range planning. The Federal-aid Airport Program is now in gear to go along with most airport sponsors as they look to—and plan for—the future.

PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW) divisions. Papers sponsored by the Board of Direction are identified by the symbols (BD). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper numbers are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 861 is identified as 861 (SM1) which indicates that the paper is contained in issue 1 of the Journal of the Soil Mechanics and Foundations Division.

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MAY: 679(ST), 680(ST), 681(ST), 682(ST)[c], 683(ST), 684(ST), 685(SA), 686(SA), 687(SA), 688(SA), 689(SA)[c], 690(EM), 691(EM), 692(EM), 693(EM), 694(EM), 695(EM), 696(PO), 697(PO), 698(SA), 699(PO)[c], 700(PO), 701(ST)[c].

JUNE: 702(HW), 703(HW), 704(HW)[c], 705(IR), 706(IR), 707(IR), 708(IR), 709(HY)[c], 710(CP), 711(CP), 712(CP), 713(CP)[c], 714(HY), 715(HY), 716(HY), 717(HY), 718(SM)[c], 719(HY)[c], 720(AT), 721(AT), 722(SU), 723(WW), 724(WW), 725(WW), 726(WW)[c], 727(WW), 728(IR), 729(IR), 730(SU)[c], 731(3U).

JULY: 732(ST), 733(ST), 734(ST), 735(ST), 736(ST), 737(PO), 738(PO), 739(PO), 740(PO), 741(PO), 742(PO), 743(HY), 744(HY), 745(HY), 746(HY), 747(HY), 748(HY)[c], 749(SA), 750(SA), 751(SA), 752(SA)[c], 753(SM), 754(SM), 755(SM), 756(SM), 757(SM), 758(CO)[c], 759(SM)[c], 760(WW)[c].

AUGUST: 761(BD), 762(ST), 763(ST), 764(ST), 765(ST)[c], 766(CP), 767(CP), 768(CP), 769(CP), 770(CP), 771(EM), 772(EM), 773(SA), 774(EM), 775(EM), 776(EM)[c], 777(AT), 778(AT), 779(SA), 780(SA), 781(SA), 782(SA)[c], 783(HW), 784(HW), 785(CP), 786(ST).

SEPTEMBER: 787(PO), 788(IR), 789(HY), 790(HY), 791(HY), 792(HY), 793(HY), 794(HY)[c], 795(EM), 796(EM), 797(EM), 798(EM), 799(EM)[c], 800(WW), 801(WW), 802(WW), 803(WW), 804(WW), 805(WW), 806(HY), 807(PO)[c], 808(IR)[c].

OCTOBER: 809(ST), 810(HW)[c], 811(ST), 812(ST)[c], 813(ST)[c], 814(EM), 815(EM), 816(EM), 817(EM), 818(EM), 819(EM)[c], 820(SA), 821(SA), 822(SA)[c], 823(HW), 824(HW).

NOVEMBER: 825(ST), 826(HY), 827(ST), 828(ST), 829(ST), 830(ST), 831(ST)[c], 832(CP), 833(CP), 834(CP), 835(CP)[c], 836(HY), 837(HY), 838(HY), 839(HY), 840(HY), 841(HY)[c].

DECEMBER: 842(SM), 843(SM)[c], 844(SU), 845(SU)[c], 846(SA), 847(SA), 848(SA)[c], 849(ST)[c], 850(ST), 851(ST), 852(ST), 853(ST), 854(CO), 855(CO), 856(CO)[c], 857(SU), 858(BD), 859(BD), 860(BD).

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JANUARY: 861(SM1), 862(SM1), 863(EM1), 864(SM1), 865(SM1), 866(SM1), 867(SM1), 868(HW1) 869(ST1), 870(EM1), 871(HW1), 872(HW1), 873(HW1), 874(HW1), 875(HW1), 876(EM1)[c], 877 (HW1)[c], 878(ST1)[c].

FEBRUARY: 879(CP1), 880(HY1), 881(HY1)[c], 882(HY1), 883(HY1), 884(IR1), 885(SA1), 886(CP1), 887(SA1), 888(SA1), 889(SA1). 890(SA1), 891(SA1), 892(SA1), 893(CP1), 894(CP1), 895(PO1) 896(PO1), 897(PO1), 898(PO1), 899(PO1), 900(PO1), 901(PO1), 902(AT1)[c], 903(IR1)[c], 904 (PO1)[c], 905(SA1)[c].

MARCH: 906(WW1), 907(WW1), 908(WW1), 909(WW1), 910(WW1), 911(WW1), 912(WW1), 913 (WW1)[c], 914(ST2), 915(ST2), 916(ST2), 917(ST2), 918(ST2), 919(ST2), 920(ST2), 921(SU1), 922(SU1), 923(SU1), 924(ST2)[c].

APRIL: 925(WW2), 926(WW2), 927(WW2), 928(SA2), 929(SA2), 930(SA2), 931(SA2), 932(SA2)[c], 933(SM2), 934(SM2), 935(WW2), 936(WW2), 937(WW2), 938(WW2), 939(WW2), 940(SM2), 941 (SM2), 942(SM2)[c], 943(EM2), 944(EM2), 945(EM2), 946(EM2)[c], 947(PO2), 948(PO2), 949(PO2), 950(PO2), 951(PO2), 952(PO2)[c], 953(HY2), 954(HY2), 955(HY2)[c], 956(HY2), 957(HY2), 958 (SA2), 959(PO2), 960(PO2).

MAY: 961(IR2), 962(IR2), 963(CP2), 964(CP2), 965(WW3), 966(WW3), 967(WW3), 968(WW3), 969 (WW3), 970(ST3), 971(ST3), 972(ST2)[c], 973(ST3), 974(ST3), 975(WW3), 976(WW3), 977(IR2), 978(AT2), 979(AT2), 980(AT2), 981(IR2), 982(IR2)[c], 983(HW2), 984(HW2), 985(HW2)[c], 986(ST3), 987(AT2), 988(CP2), 989(AT2).

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c. Discussion of several papers, grouped by Divisions.

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